

STATE OF COLORADO

Bill Ritter, Jr., Governor

DEPARTMENT OF NATURAL RESOURCES

DIVISION OF WILDLIFE

AN EQUAL OPPORTUNITY EMPLOYER

Thomas E. Remington, Director

6060 Broadway

Denver, Colorado 80216

Telephone: (303) 297-1192

wildlife.state.co.us



*For Wildlife-
For People*

December 10, 2010

Ms. Linda Bassi

Colorado Water Conservation Board

Stream and Lake Protection Section

1313 Sherman Street, Room 723

Denver, Colorado 80203

Re: Colorado Division of Wildlife Instream Flow Recommendations for the San Miguel River.

Dear Linda,

The purpose of this letter is to formally transmit the Colorado Division of Wildlife's (CDOW) Instream Flow Recommendations for San Miguel River. The importance of this stream reach has led to cooperation between the Bureau of Land Management (BLM) and the CDOW to document the natural environment in this stream reach and to implement cooperative studies to determine the flow rates needed to support the natural environment.

This portion of the river is known to provide habitat for flannelmouth sucker, bluehead sucker, and roundtail chub. The BLM and CDOW are signatories to a multi-state conservation agreement designed to protect and enhance habitat for these species, with the objective of preventing a listing of these species under the Endangered Species Act. Establishment of instream flow protection for streams known to provide habitat for the three species is identified as a priority conservation action under this agreement.

The lower San Miguel River is also known to provide habitat for globally imperiled riparian communities and other important riparian communities, because of the free-flowing hydrology of the river. These globally impaired communities include New Mexico Privet riparian shrubland and Skunkbrush riparian shrubland. Other important riparian communities include Narrowleaf Cottonwood Communities and Fremont Cottonwood communities. The Colorado Natural Heritage Program has identified two potential conservation areas along this reach of the river because of these riparian communities and species.

The CDOW and BLM believe that instream flow protection for these values can be achieved while allowing water to be developed for current and future needs, including municipal, industrial and agricultural uses. Almost three years have elapsed since the BLM and CDOW provided an initial flow recommendation to the Colorado Water Conservation Board (CWCB), in the form of a draft instream flow report. In those three years, BLM, CWCB and CDOW staff members have attended multiple public meetings within the watershed to explain the instream flow proposal and its potential impact of

DEPARTMENT OF NATURAL RESOURCES, Mike King, Executive Director

WILDLIFE COMMISSION, Tim Glenn, Chair • Robert Streeter, Vice Chair • Mark Smith, Secretary

Members, David R. Brougham • Dennis Buechler • Dorothea Farris • Allan Jones • John Singletary • Dean Wingfield

Ex Officio Members, Mike King and John Stulp

future water supplies. BLM and CDOW have also provided all of the supporting data to interested parties for their review and have worked with several stakeholders to try and address their specific concerns regarding the instream flow recommendation. Water users within the San Miguel watershed have had three years to study their long-term water supply needs and to file water rights applications to meet those needs. Given the long-term effort to engage the public and water users, the CDOW requests that the CWCB proceed with its appropriation process at the regularly scheduled board meeting in January 2011.

The information contained in the attached report forms the basis for the instream flow recommendation to be considered by the Board. It is the CDOW staff's opinion that the information is sufficient for the Board to begin the findings required in Rule 5 (i) of the Instream Flow Rules.

If you have any questions regarding the attached information or the instream flow recommendations, please contact me at (303)-291-7267.

Sincerely,



Mark Uppendahl
Colorado Division of Wildlife
Instream Flow Program Coordinator

Cc: Grady McNeill, CDOW Resource Support Section Manager – w/o attachments
Jay Skinner, CDOW Water Unit Program Manager – w/o attachments
Dave Graf, CDOW Water Resource Specialist – w/o attachments
John Alves, CDOW Senior Fish Biologist – w/o attachments
Dan Kowalski, CDOW Fish Biologist – w/o attachments



United States Department of the Interior

BUREAU OF LAND MANAGEMENT

Colorado State Office
2850 Youngfield Street
Lakewood, Colorado 80215-7093
www.blm.gov/co



In Reply Refer To:
7250 (CO-932)

DEC 15 2010

Ms. Linda Bassi
Colorado Water Conservation Board
1313 Sherman Street, Room 721
Denver, Colorado 80203

Dear Ms. Bassi:

The Bureau of Land Management (BLM) is writing this letter to formally communicate its instream flow recommendation for the San Miguel River, between the confluence with Calamity Draw and the confluence with the Dolores River. The importance of this stream reach has led to cooperation between the BLM and the Colorado Division of Wildlife (CDOW) to document the natural environment in this stream reach and to implement cooperative studies to determine the flow rates needed to support the natural environment.

This portion of the river is known to provide habitat for flannemouth sucker, bluehead sucker, and roundtail chub. The BLM and the CDOW are signatories to a multi-state conservation agreement designed to protect and enhance habitat for these species, with the objective of preventing a listing of these species under the Endangered Species Act. Establishment of instream flow protection for streams known to provide habitat for the species is identified as a priority conservation action under this agreement.

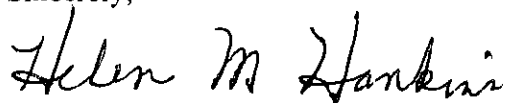
The lower San Miguel River is also known to provide habitat for globally imperiled riparian communities and other important riparian communities, because of the free-flowing hydrology of the river. These globally imperiled communities include New Mexico privet riparian shrubland and skunkbrush riparian shrubland. Other important riparian communities include narrowleaf cottonwood communities and Fremont cottonwood communities. The Colorado Natural Heritage Program has identified two potential conservation areas along this reach of the river because of these riparian communities and species.

BLM believes that instream flow protection for these values can be achieved while allowing water to be developed for current and future needs, including municipal, industrial, and agricultural uses. Almost three years have elapsed since the BLM and the CDOW provided an initial flow recommendation to the Colorado Water Conservation Board (CWCBC), in the form of a draft instream flow report. In those three years, the BLM, the CDOW, and the CWCBC staff

members have attended multiple public meetings within the watershed to explain the instream flow proposal and its potential impact on future water supplies. The BLM and the CDOW have also provided all of the supporting data to interested parties for their review and have worked with several stakeholders to address their specific concerns regarding the instream flow recommendation. Water users within the San Miguel watershed have had three years to study their long-term water supply needs and to file water rights applications to meet those needs. Given the long-term effort to engage the public and water users, the BLM requests that the CWCB proceed with its appropriation process at the regularly scheduled board meeting in January 2011.

The enclosures to this letter provide specific information with regard to recommended flow rates, habitat analysis, biological characteristics, and water availability. If you have any questions regarding this formal recommendation, please contact Roy Smith at (303) 239-3940.

Sincerely,

A handwritten signature in black ink that reads "Helen M. Hankins". The signature is written in a cursive, flowing style.

Helen M. Hankins
State Director

cc:

Barbara Sharrow, Uncompahgre Field Office
Valori Armstrong, Southwest District

Enclosure 1- San Miguel River Instream Flow Recommendation

Biological Summary

Fisheries

Fishery surveys taken during 2001 and 2008 by the Colorado Division of Wildlife (CDOW) indicate that the stream environment supports bluehead sucker (*Catostomus discobolus*), flannelmouth sucker *Catostomus latipinnis*, mottled sculpin (*Cottus bairdi*), roundtail chub (*Gila robusta*), speckled dace (*Rhinichthys osculus*), and white sucker (*Catostomus commersoni*). The surveys indicated that 71% of the fish captured were either bluehead sucker, flannelmouth sucker, and roundtail chub, and that all of these species were represented by individuals of multiple age classes. This reach of the San Miguel River appears to be one of the best populations of the two native suckers within the Dolores River watershed and contains much larger individuals than most sites on the Dolores River.

Roundtail chub (*Gila robusta*) is recognized by the State of Colorado as a species of special concern. The roundtail chub, flannelmouth sucker (*Catostomus latipinnis*) and bluehead sucker (*Catostomus discobolus*) are considered sensitive species by the Bureau of Land Management (BLM). Criteria that apply to the BLM sensitive species include the following: 1) species under status review by the U.S. Fish and Wildlife Service; or 2) species with numbers declining so rapidly that federal listing may become necessary; or 3) species with typically small and widely dispersed populations; or 4) species inhabiting ecological refugia or other specialized or unique habits.

The CDOW, the BLM and others have developed a "Range-Wide Conservation Agreement and Strategy" to direct management for these species. This plan provides direction and goals for research and management of projects. The success of management strategies will depend upon the voluntary implementation of these strategies by the signatories. Special attention will need to be given to habitat degradation and influence of non-native species interactions within the native range of these species. The intention of these plans is to increase populations and distributions of identified species, thereby assisting in the long-term persistence of each species. The success of such plans could potentially curtail the need for federal listing of these species under the Endangered Species Act (ESA). These species are not currently federally listed.

Macroinvertebrates

The BLM has been collecting aquatic invertebrate samples for several years at several sites within the proposed instream flow reach. These sites include the San Miguel upstream of the Dolores River, at Tabeguache Creek and upstream of Tabeguache Creek. These surveys indicate that, relative to other streams within the Colorado Plateau region, this stream segment exhibits index readings that are significantly above average for macroinvertebrate abundance, diversity, and number of macroinvertebrate families. Even though macroinvertebrate populations were severely impacted by the 2002 drought, by 2003 this stream reach had already recovered to average levels for macroinvertebrate abundance and diversity, indicating the resilience of this stream reach.

Riparian Community

In addition to the the globally impaired New Mexico privet riparian shrubland and skunkbrush riparian shrubland communities, this section of the San Miguel River contains very high quality examples of several other species and communities. Other species include narrowleaf cottonwood, Fremont cottonwood, coyote willow, river birch, skunkbrush, and silver buffaloberry. These communities are in good condition because of the largely intact natural hydrology and relatively low number of invasive species in the riparian zone, relative to other rivers in the western United States. The riparian communities are directly dependent on flows within the river segment to provide periodic flooding and to maintain groundwater levels within the root zone.

Enclosure 2- San Miguel River Instream Flow Recommendation

Flow Quantification Methodology

PHABSIM and R2Cross Methodology

The Colorado Division of Wildlife (CDOW) and the Bureau of Land Management (BLM) evaluated all of the data collected to date and determined that best flow recommendation would come from using the results from a combination of methods. Physical Habitat Simulation (PHABSIM) is a widely accepted method for quantifying the suitable versus unsuitable hydraulic habitat attributes of selected species and life stages as a function of discharge. The R2CROSS is best suited for identifying flows with specific hydraulic criteria across riffle type habitats. The State of Colorado has used the R2CROSS extensively in the past to appropriate instream flow water rights. The CDOW and the BLM were concerned that exclusive use of the standard R2CROSS method may not be appropriate for this reach of the San Miguel River due to its major width (over 75' wide in most places), type of fish species present (warm/cool water species) and its big river channel hydraulics and characteristics.

The CDOW and the BLM collected transect and flow data for seven different cross-sections within an 815-foot reach of stream. The transect data was collected at a site approximately 1.5 miles upstream from the confluence of the San Miguel River with Tabeguache Creek. These seven transects incorporated different mesohabitat types including riffles, runs, pools and glides. These seven different cross-sections formed the basis for the PHABSIM/River Habitat Simulation (RHABSIM) study conducted by the CDOW and the BLM. The PHABSIM is widely used in North America to quantify instream flow regimes and consists of two modeling components.

These initial recommendations are designed to address the unique biologic requirements of this stream reach without regard to water availability. In addition to the criteria developed using the PHABSIM Methodology and the RHABSIM Software, the three standard instream flow hydraulic parameters used in the R2CROSS (average depth, percent wetted perimeter and average velocity) were also used to calculate and predict the biologic instream flow recommendations.

Application of Habitat Suitability Criteria

Habitat Suitability Criteria (HSC) were developed from the 2003 Riverine Fish Flow Investigation Study Report (Federal Aid Project F-289-R6) written and performed by Richard Anderson, CDOW Aquatic Researcher, and Gregory Stewart, Department of Geosciences Oregon State University¹. The basis for this study was a 1999 request from the Colorado Water Conservation Board (CWCB) for the CDOW to provide biologically justified instream flow

¹ See "Impacts of stream flow alterations on native fish abundance and native fish habitat and the use of native fish population data to support instream flow recommendations made using a 2D instream flow methodology."

recommendations for the Yampa and Colorado Rivers based on habitat and flow requirements for non-endangered native fish. Anderson and Stewart used two-dimensional (2D) modeling to develop habitat suitability criteria for bluehead and flannemouth suckers, two native species. Their methods and results are more fully described in Anderson and Stewart (2003) and Stewart and Anderson (2005) and (2006).

The bluehead and flannemouth sucker habitat suitability criteria were used to develop specific hydraulic criteria that were incorporated into a PHABSIM/RHABSIM analysis. Stewart and Anderson determined that "Abundance of bluehead sucker was a reliable indicator for instream flows and habitat maintenance for the native fish assemblage. In the Colorado, Gunnison, and Yampa Rivers, bluehead sucker habitat peaked at flows of 600 to 1,200 cfs. This flow range also resulted in high habitat diversity and high native fish biomass. Their assumption that flows that maintained adequate bluehead sucker abundance (about 25% of fish over 15 cm) would also maintain adequate flannemouth sucker and roundtail chub habitat was validated by this study."

The CDOW and the BLM determined for this flow recommendation that the bluehead sucker would be the primary indicator species for the biologically based instream flow recommendation with the flannemouth sucker being the secondary indicator species. The main reason for this is bluehead sucker abundance is directly related to availability and quality of riffle habitats. The primary objective of most cross section methodologies, including the R2CROSS, is to maintain quality riffles. Riffles are the most vulnerable habitat to dewatering and riffles are important for invertebrate productivity. When riffle habitats are maintained there should be sufficient habitats for perpetuating carrying capacity (biomass) and composition for all members of the native fish assemblage (Nehring 1979). To verify the flow recommendations, the CDOW and the BLM compared results from their PHABSIM/RHABSIM study with results using the R2CROSS Methodology with standard criteria.

Enclosure 3- San Miguel River Instream Flow Recommendation

Biological Flow Recommendations

Overview of Recommended Flow Rates

The Bureau of Land management (BLM) and the Colorado Division of Wildlife (CDOW) are recommending 325 cubic feet per second, high flow period (spring/summer), and 115 cubic feet per second, low flow period (fall/winter), based on their data collection efforts. These flow recommendations are based on the physical and biological data collected to date and do not incorporate any water availability constraints.

- 325 cubic feet per second is required to maintain a reasonable amount of bluehead and flannelmouth sucker usable spring and summer habitat, in addition to maintaining the three principal hydraulic criteria of average depth, average velocity and percent wetted perimeter at adequate levels.
- 115 cubic feet per second is required to maintain a reasonable amount of bluehead and flannelmouth sucker usable fall and winter habitat, in addition to maintaining two of the three principal hydraulic criteria.

The recommended flow values were determined using the best professional judgment of the CDOW and the BLM biologists and hydrologists. The CDOW and the BLM professionals reviewed and evaluated the results of the Physical Habitat Simulation (PHABSIM) Methodology and River Habitat Simulation (RHABSIM) software PHABSIM/RHABSIM analysis. They also reviewed the R2CROSS analysis, using standard hydraulic criteria.

The BLM and the CDOW staff compared results from their PHABSIM/RHABSIM data analysis with their R2CROSS analysis. Using the results from the PHABSIM/RHABSIM data analysis, the maximum amount of usable habitat for bluehead suckers was produced at a flow of 500 cfs and for flannelmouth suckers at a flow of 325 cfs. The R2CROSS analysis indicated that a spring/summer flow of approximately 650 cfs was necessary to meet all three of the critical hydraulic criteria at this site and a fall/winter flow of 115 cfs would meet 2 of 3 of the hydraulic criteria.

Comparison of PHABSIM and R2Cross Results

The CDOW and the BLM are recommending that a flow of 325 cfs, for the time period of April 15 through June 14, is the minimum amount necessary to preserve the natural environment to a reasonable degree, for this reach of the San Miguel River. This is based on the assumption that 325 cfs would preserve 90% of the weighted useable area available to the bluehead sucker and 100% of the weighted useable area available to the flannelmouth sucker. BLM and CDOW hydrologists and biologists also believe a flow that maintains adequate bluehead and flannelmouth sucker habitat should also maintain adequate roundtail chub habitat.

The spring/summer flow of 325 cfs was reduced to 170 cfs for the June 15 through July 31 time period because of water availability concerns. The instream flow recommendation of 170 cfs was derived to maximize the existing bluehead and flannelmouth sucker habitat available under a declining hydrograph, by maintaining an average depth of 1.0 foot over the measured riffle cross-section. An average depth of 1.0 foot combined with average velocities exceeding 1.3 ft/sec, were determined to be marginally suitable bluehead sucker habitat (see Anderson & Stewart Report).

Because the PHABSIM/RHABSIM data only quantified suitable versus unsuitable hydraulic habitat as a function of discharge, the CDOW and the BLM staff used the results of the R2CROSS Method to develop the fall/winter instream flow recommendation of 115 cfs. The R2CROSS Method suggests that fall/winter flows should maintain at least 2 of 3 of the identified critical hydraulic criteria. At the Cross Section #1 site, 115 cfs meets 2 of 3 criteria (average depth and velocity) by providing on average, 0.8 feet of depth and velocities well over 1.0 ft/sec. The fall/winter flow recommendation was further reduced to 80 cfs, for the time period of September through February, due to water availability concerns. It should be noted however, that 80 cfs still maintains adequate velocity (approximately 2.5 ft/sec), a wetted perimeter of almost 60% and an average depth of nearly 0.7 feet.

Enclosure 4- San Miguel River Instream Flow Recommendation

Water Availability

The Bureau of Land management (BLM) and Colorado Division of Wildlife (CDOW) staff conducted an evaluation of the stream hydrology to determine if water was physically available for the instream flow recommendation. The hydrograph below was derived from data collected by the United States Geological Survey (USGS) stream gage for the San Miguel River at Uravan, CO (#09177000), which has a drainage area of 1500 square miles (See Gage Summary in Appendix C). The total drainage area of this segment of the San Miguel River is approximately 1500 square miles. The period of record for this gage was 1954 to 2004, the period of record used by staff in their analysis was 1954 - 2004, or 50 years of record. Table 2 below displays the estimated flow of the San Miguel River at the gage, in terms of a percentage of exceedence.

Exceedences	January	February	March	April	May	June	July	August	September	October	November	December
1%	162.9	351	1044	3750	4123	2808	1770	958.5	612	432	370.6	217.8
5%	140	186.1	578.2	2610	2700	2240	1102	597.2	371	292.1	212	160
10%	130	155.7	383.2	1900	2220	1770	868	424.7	301	252	182	148
20%	120	130	252	1260	1724	1380	633.4	265.6	201	199	152	121
50%	80	97	128	550	943	820	301	125.5	88	116	100	85
80%	62	70	83	233	484	437	112	51.2	42	76.6	73	65
90%	55	61	70.8	130	271	298	61	27	29	53.8	61	57
95%	48	55	62	96	140.9	215	34	20.55	23	33	52	50
99%	40	40.73	47	55	61.9	38	6.63	5.91	14	20	32	36

Table 2: Estimated Stream Flow for SAN MIGUEL RIVER

Table 2 shows that the spring flow recommendation of 325 cfs, is available at least 50% of the time, April 15 through June 30. The high flow summer recommendation of 170 cfs, is available at least 50% of the time, July 1 through July 31. The low flow summer recommendation of 115 cfs, is available at least 50% of the time, August 1 through August 31 and March 1 through April 14. The winter recommendation of 80 cfs, based on water availability concerns, is available at least 50% of the time, September 1 through February 29. However, if additional water is determined to be available in further investigations, the CDOW and the BLM would recommend enlarging the wintertime recommendation up to 115 cfs, to preserve the natural environment to a reasonable degree.

Stream: SAN MIGUEL RIVER

Executive Summary

Water Division: 4
Water District: 60
CDOW#: 46842

Segment: CALAMITY DRAW to DOLORES RIVER

Upper Terminus: CALAMITY DRAW

Latitude: 38° 15' 24.0"N Longitude: 108° 36' 49.5"W

Lower Terminus: DOLORES RIVER

Latitude: 38° 22' 47.1"N Longitude: 108° 48' 12.3"W

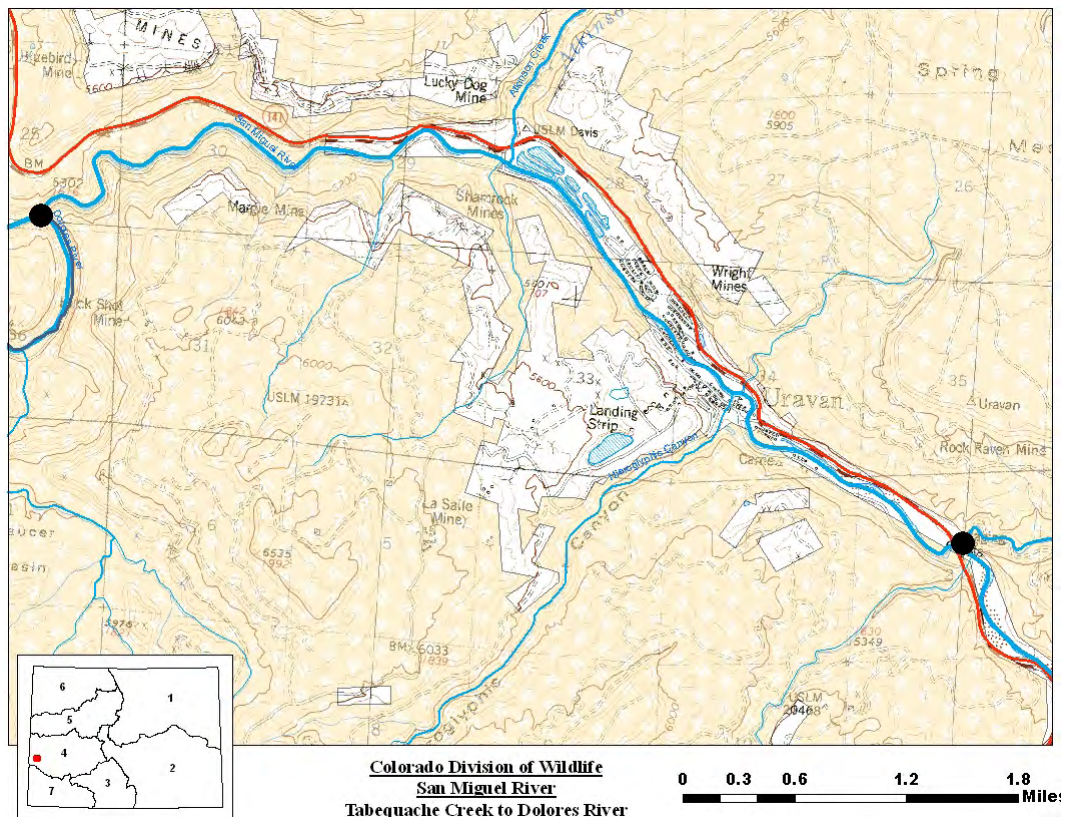
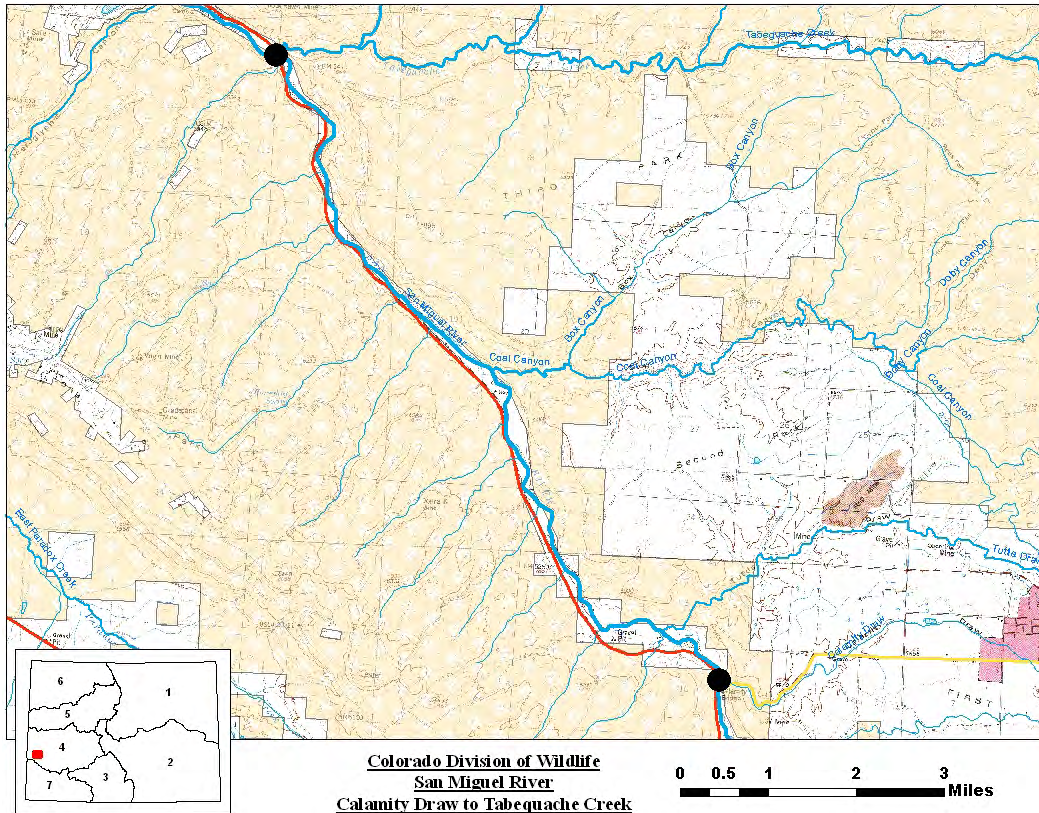
Counties: Montrose County

Length: 16.5 miles

USGS Quad(s):

ISF Appropriation: 325 cfs (04/15 – 06/14) – (Uravan Gage)
 170 cfs (06/15 – 07/31)
 115 cfs (08/01 – 08/31)
 80 cfs (09/01 – 02/28)
 115 cfs (03/01 – 04/14)





The information contained in this report and the associated instream flow file folder forms the basis for the instream flow recommendation to be considered by the Colorado Water Conservation Board (Board). It is the Colorado Division of Wildlife (CDOW) and Bureau of Land Management (BLM) staff's opinion that the information contained in this report is sufficient to support the findings required in Rule 5(i).

The State of Colorado's Instream Flow Program (ISFP) was created in 1973 when the Colorado State Legislature recognized "the need to correlate the activities of mankind with some reasonable preservation of the natural environment" (See §37-92-102 (3) C.R.S.). The statute vests the Board with the exclusive authority to appropriate and acquire instream flow and natural lake level water rights. In order to encourage other entities to participate in Colorado's ISFP, the statute directs the Board to request instream flow recommendations from other state and federal agencies. The CDOW & BLM are jointly recommending this segment of San Miguel River to the Board for inclusion into the ISFP. The San Miguel River is being considered for inclusion into the ISFP because it has a natural environment that can be preserved to a reasonable degree with an instream flow water right.

The CDOW is forwarding this instream flow recommendation to the Board to meet Colorado's policy "... that the wildlife and their environment are to be protected, preserved, enhanced, and managed for the use, benefit, and enjoyment of the people of this state and its visitors ... and that, to carry out such program and policy, there shall be a continuous operation of planning, acquisition, and development of wildlife habitats and facilities for wildlife-related opportunities" (See §33-1-101 (1) C.R.S.). The CDOW Strategic Plan states "[h]ealthy aquatic environments are essential to maintain healthy and viable fisheries, and critical for self-sustaining populations. The [CDOW] desires to protect and enhance the quality and quantity of aquatic habitats."

The Bureau of Land Management is forwarding this instream flow recommendation to the Board because it is strongly interested in instream flow protection for the lower San Miguel River for multiple reasons. First, this portion of the river is known to provide habitat for flannemouth sucker, bluehead sucker, and roundtail chub. The BLM, CDOW and others have signed a multi-state conservation agreement designed to protect and enhance habitat for these species, with the objective of preventing a listing of these species under the Endangered Species Act (see Appendix A). Establishment of instream flow protection for streams known to provide habitat for the species is identified as a priority conservation action under this agreement.

Second, the lower San Miguel River is known to provide habitat for globally imperiled riparian communities and other important riparian communities, because of the free-flowing hydrology of the river. These globally impaired communities include New Mexico Privet riparian shrubland and Skunkbrush riparian shrubland. Other important riparian communities include Narrowleaf Cottonwood Communities and Fremont Cottonwood communities. The Colorado Natural Heritage Program has identified two potential conservation areas along this reach of the river because of these riparian communities and species (see Appendix B). Finally, BLM seeks to protect flows that support reclaimed acreage from the Umetco Superfund site. The reclamation effort is now complete, and the flows assist in maintaining the ecology of land parcels that were donated by Umetco as part of the Superfund settlement.

General Information

The San Miguel River is approximately 70 miles long. It begins on the north side of Wasatch Mountain at an elevation of approximately 9100 feet and terminates at the confluence with the Dolores River at an elevation of approximately 4900 feet. Of the 16.5 mile segment addressed by this report, approximately 28% of the segment, or 4.6 miles, is located on public lands. The San Miguel River is located within San Miguel and Montrose Counties. The total drainage area of the San Miguel River is approximately 1,500 square miles. The San Miguel River generally flows in a westerly direction. The San Miguel Basin is the largest tributary to the Dolores River and is part of the Upper Colorado River System. The one million acre San Miguel Basin is about 60 percent semi-arid rangeland and agricultural land, both comprising the lower elevations. The remaining 40 percent of the basin is in higher elevation, forested subalpine and alpine zones of the San Juan Mountains. Most of the flow in the San Miguel River (240,000 acre-feet per year) is derived from snowmelt at the higher elevations. Because of its relatively low, human population density and lack of large, water storage impoundments, the San Miguel Basin is considered to be one of the few ecologically and hydrologically intact river basins in Colorado.

The subject of this report is two segments of the San Miguel River. The first segment begins at the confluence with Calamity Draw and extends downstream to the confluence with Tabeguache Creek. The second segment begins at Tabeguache Creek and extends downstream to the confluence with the Dolores River. The proposed segments are located west of the towns of Nucla and Naturita. The instream flow recommendation for both segments is discussed below.

Species of Special Concern and Sensitive Species

Roundtail chub (*Gila robusta*) is recognized by the State of Colorado as a species of special concern. The roundtail chub, flannelmouth sucker (*Catostomus latipinnis*) and bluehead sucker (*Catostomus discobolus*) are considered sensitive species by the BLM. Criteria that apply to BLM sensitive species include the following: 1) species under status review by the U.S. Fish and Wildlife Service; or 2) species with numbers declining so rapidly that federal listing may become necessary; or 3) species with typically small and widely dispersed populations; or 4) species inhabiting ecological refugia or other specialized or unique habits.

The CDOW, BLM and others have developed a “Range-wide conservation agreement and strategy” to direct management for these species. This plan provides direction and goals for research and management of projects. The success of management strategies will depend upon the voluntary implementation of these strategies by the signatories. Special attention will need to be given to habitat degradation and influence of non-native species interactions within the native range of these species. The intention of these plans is to increase populations and distributions of identified species, thereby assisting in the long-term persistence of each species. The success of such plans could potentially curtail the need for federal listing of these species under the Endangered Species Act (ESA). These species are not currently federally listed.

ROUNDTAIL CHUB

Historically, roundtail chub were known to commonly occur in most medium to large tributaries of the Upper Colorado River Basin (Vanicek 1967, Holden and Stalnaker 1975, Joseph et al. 1977). Roundtail chub historically occurred in lower elevation (below 7,546 ft.) streams, including the Colorado, Dolores, Duchesne, Escalante, Green, Gunnison, Price, San Juan, San Rafael, White, and Yampa rivers (Bezzerrides and Bestgen 2002). Roundtail chub are often found in stream reaches that have a complexity of pool and riffle habitats (Bezzerrides and Bestgen 2002). Adults are found in eddies and pools adjacent to strong current and use instream boulders as cover (Sigler and Sigler 1996, Brouder et al., 2000). Roundtail chub begin spawning when water temperatures reach about 65°F (Vanicek and Kramer 1969, Joseph et al. 1977). In most Colorado River tributaries this increase in temperature coincides with a decrease in discharge after peak runoff (Bezzerrides and Bestgen 2002).

FLANNELMOUTH SUCKER

The flannemouth sucker is a good indicator species for flow and habitat relationships (Stewart and Anderson 2006-CR1). The flannemouth sucker is a large fish reaching up to almost 2 feet in length. Historically, the flannemouth sucker was commonly found in most, if not all, medium to large, lower elevation rivers of the Upper Colorado River drainage (upstream of Glen Canyon Dam). Within the State of Colorado, flannemouth sucker are present in the Colorado River and numerous tributaries including the Gunnison River up to the Aspinall Unit reservoirs (Bezzerrides and Bestgen 2002), the Uncompahgre River (Sigler and Miller 1963) and the Dolores River. Flannemouth suckers are typically found in slower, warmer rivers in plateau regions of the Colorado River drainage (Deacon and Mize 1997). They usually inhabit the mainstem of moderate to large rivers but are occasionally found in small streams. This species frequents pools and deep runs but can also be found in the mouths of tributaries, riffles, and backwaters. Flannemouth sucker typically spawn in the Upper Colorado River basin between April and June (McAda 1977, McAda and Wydoski 1980, Snyder and Muth 1990, Tyus and Karp 1990).

BLUEHEAD SUCKER

The bluehead sucker provides the most information for justifying instream flow needs to maintain the native fish assemblage (Stewart and Anderson 2006-CR1). The bluehead sucker is a large fish reaching up to 17 inches in length. This species is found in a large variety of river systems ranging from large rivers with discharges of several thousand cfs to small creeks with less than a couple of cfs (Smith 1966). Adult bluehead suckers exhibit a strong preference for specific habitat types (Holden and Stalnaker 1975). This species has been reported to typically be found in runs or riffles with rock or gravel substrate (Vanicek 1967, Holden and Stalnaker 1975, Carlson et al. 1979, Sublette et al. 1990). The bluehead sucker is known to feed on invertebrates, which have their highest densities in riffles. Although the species generally inhabits streams with cool temperatures, bluehead suckers have been found inhabiting small creeks with water temperatures as high as 82.4° F (Smith 1966).

Instream Flow Recommendation(s)

The CDOW & BLM are recommending 325 cfs, high flow period (spring/summer), and 115 cfs, low flow period (fall/winter), based on their data collection efforts. These flow recommendations are based on the physical and biological data collected to date and do not incorporate any water availability constraints.

- 325 cubic feet per second is required to maintain a reasonable amount of bluehead and flannemouth sucker usable spring and summer habitat, in addition to maintaining the three principal hydraulic criteria of average depth, average velocity and percent wetted perimeter at adequate levels;
- 115 cubic feet per second is required to maintain a reasonable amount of bluehead and flannemouth sucker usable fall and winter habitat, in addition to maintaining two of the three principal hydraulic criteria.

The recommended flow values were determined using the best professional judgment of CDOW and BLM biologists and hydrologists. The CDOW and BLM professionals reviewed and evaluated the results of the Physical Habitat Simulation (PHABSIM) Methodology and RHABSIM software PHABSIM/RHABSIM analysis. They also reviewed the R2CROSS analysis, using standard hydraulic criteria.

Land Status Review

Upper Terminus	Lower Terminus	Total Length (miles)	Land Ownership	
			% Private	% Public
CALAMITY DRAW	TABAUCHE CREEK	10.0	85%	15%
TABAUCHE CREEK	DOLORES RIVER	6.5	52%	48%

28% of the public lands are managed by the BLM.

Biological Data

Over the past ten years, the CDOW and BLM have been collecting stream cross-section information, natural environment data, and other data needed to quantify the instream flow needs for this reach of the San Miguel River. The San Miguel River is classified as a large river (over 100 feet wide) and fishery surveys in 2001 indicate the stream environment supports: bluehead sucker (*Catostomus discobolus*), flannemouth sucker *Catostomus latipinnis*, mottled sculpin (*Cottus bairdi*), roundtail chub (*Gila robusta*), speckled dace (*Rhinichthys osculus*) and white sucker (*Catostomus commersoni*) (See CDOW Fish Survey in Appendix C).

In addition, the BLM has been collecting aquatic invertebrate samples, for several years, at several sites within the proposed instream flow reaches. These sites include the San Miguel upstream of the Dolores, at Tabeguache Creek and upstream of Tabeguache Creek (see Appendix D).

Biological and Field Survey Data

The CDOW and BLM collected transect and flow data for 7 different cross-sections within an 815 foot reach of stream. The transect data was collected at a site approximately 1.5 miles upstream from the confluence of the San Miguel River with Tabeguache Creek. These 7 transects incorporated different mesohabitat types including riffles, runs, pools and glides. These 7 different cross-sections formed the basis for the PHABSIM/RHABSIM study conducted by the CDOW and BLM. PHABSIM is widely used in North America to quantify instream flow

regimes and consists of two modeling components. The hydraulic component is a series of one-dimensional cross-sections that are linked to produce a series of rectangular cells that form a grid. Mean depth and velocity conditions are calculated for each cell for a given flow. The biological component is a set of suitability index curves for depth and velocity criteria that are used to rate micro-habitat suitability for each cell in the cross-sectional grid. Habitat availability is measured by an index called weighted useable area (WUA)¹, the summation of cell areas weighted by its suitability index. When plotted versus discharge WUA typically peaks at a single flow that is considered the flow that maximizes habitat. Please see Appendix E for more information on the PHABSIM Methodology.

For this study, 7 one-dimensional cross-sections were linked to produce the series of rectangular cells that formed the grid to estimate WUA. Mean depth and velocity conditions were calculated for each cell at 4 different measured flows (100, 175, 325 and 450 cfs). Habitat suitability criteria (HSC) were developed from the 2003 Riverine Fish Flow Investigation Study Report (Federal Aid Project F-289-R6) written and performed by Richard Anderson, CDOW Aquatic Researcher, and Gregory Stewart, Department of Geosciences Oregon State University² (See Appendix F). The basis for this study was a 1999 request from the CWCB for the CDOW to provide biologically justified instream flow recommendations for the Yampa and Colorado Rivers based on habitat and flow requirements for non-endangered native fish. Anderson and Stewart used two-dimensional (2D) modeling to develop habitat suitability criteria for bluehead and flannelmouth suckers, two native species. Their methods and results are more fully described in Anderson and Stewart (2003) and Stewart and Anderson (2005) and (2006).

The bluehead and flannelmouth sucker habitat suitability criteria were used to develop specific hydraulic criteria that were incorporated into a PHABSIM/RHABSIM analysis.. Stewart and Anderson determined that “Abundance of bluehead sucker was a reliable indicator for instream flows and habitat maintenance for the native fish assemblage. In the Colorado, Gunnison and Yampa Rivers bluehead sucker habitat peaked at flows of 600 to 1,200 cfs. This flow range also resulted in high habitat diversity and high native fish biomass. Their assumption that flows that maintained adequate bluehead sucker abundance (about 25% of fish over 15 cm) would also maintain adequate flannelmouth sucker and roundtail chub habitat was validated by this study.”

CDOW and BLM determined for this flow recommendation that the bluehead sucker would be the primary indicator species for the biologically based instream flow recommendation with the flannelmouth sucker being the secondary indicator species. The main reason for this is bluehead sucker abundance is directly related to availability and quality of riffle habitats. The primary objective of most cross section methodologies, including R2CROSS, is to maintain quality riffles. Riffles are the most vulnerable habitat to dewatering and riffles are important for invertebrate productivity. When riffle habitats are maintained there should be sufficient habitats for perpetuating carrying capacity (biomass) and composition for all members of the native fish assemblage (Nehring 1979). To verify the flow recommendations, CDOW and BLM compared results from their PHABSIM/RHABSIM study with results using the R2CROSS Methodology with standard criteria (see Appendix F).

¹ No Channel Material Indexes were used to quantify the WUA in this report.

² See “Impacts of stream flow alterations on native fish abundance and native fish habitat and the use of native fish population data to support instream flow recommendations made using a 2D instream flow methodology.”

Transect 1 was located within a typical riffle section and was used in a standard R2CROSS analysis. The modeling results from these efforts are within the confidence interval produced by the R2CROSS model (see Table 1).

Biological Flow Recommendation

CDOW and BLM staff, using a combination of PHABSIM/RHABSIM and R2CROSS methodologies, developed the proposed instream flow recommendations for the San Miguel River (see Appendix H for copies of the hydraulic modeling data). Board staff relied upon the biological expertise of the cooperating agencies to interpret the output from the PHABSIM/RHABSIM and R2CROSS Methodologies to develop the initial, biologic instream flow recommendations.

These initial recommendations are designed to address the unique biologic requirements of each stream without regard to water availability. In addition to the criteria developed using the PHABSIM Methodology and RHABSIM Software, the three standard instream flow hydraulic parameters used in R2CROSS (average depth, percent wetted perimeter and average velocity) were also used to calculate and predict the biologic instream flow recommendations (see Table 1 Below).

For this segment of stream, several data sets were collected with the results shown in Table 1 below. Table 1 shows who collected the data (Party), the measured discharge at the time of the surveys (Q), the accuracy range of the predicted flows based on Manning's Equation (240% and 40% of Q), the method used, the summer flow recommendation based on meeting 3 of 3 hydraulic criteria and the winter flow recommendation based upon 2 of 3 hydraulic criteria.

Table 1: Data

Party	Measured Q's	250%-40%	Method	Summer (3/3)	Winter (2/3)
DOW & BLM	450, 325, 175, 100	1125 - 40	PHABSIM / RHABSIM	500 (Bluehead) 325 (Flannelmouth) ³	---
DOW & BLM	450, 325, 175, 100	1125 - 40	R2X Standard	650	115

DOW = Division of Wildlife; BLM = Bureau of Land Management

Biologic Flow Recommendation

The CDOW and BLM evaluated all of the data collected to date and determined that best flow recommendation would come from using the results from a combination of methods. PHABSIM is a widely accepted method for quantifying the suitable versus unsuitable hydraulic habitat attributes of selected species and life stages as a function of discharge. R2CROSS is best suited for identifying flows with specific hydraulic criteria across riffle type habitats. The State of Colorado has used R2CROSS extensively in the past to appropriate instream flow water rights.

³ The PHABSIM/RHABSIM analysis was used to only quantify the suitable versus unsuitable hydraulic habitat attributes of bluehead and flannelmouth sucker adults as a function of discharge. Amounts shown reflect the discharge which produced the maximum amount of useable habitat based on the measured mesohabitat types.

CDOW and BLM were concerned that the standard R2CROSS method may not be appropriate for this reach of the San Miguel River due to its major width (over 75' wide in most places), type of fish species present (warm/cool water species) and its big river channel hydraulics and characteristics.

Accordingly, BLM and CDOW staff compared results from their PHABSIM/RHABSIM data analysis with their R2CROSS analysis. Using the results from the PHABSIM/RHABSIM data analysis, the maximum amount of usable habitat for bluehead suckers was produced at a flow of 500 cfs and for flannemouth suckers at a flow of 325 cfs. The R2CROSS analysis indicated that a spring/summer flow of approximately 650 cfs was necessary to meet all three of the critical hydraulic criteria at this site and a fall/winter flow of 115 cfs would meet 2 of 3 of the hydraulic criteria.

CDOW and BLM are recommending that a flow of 325 cfs, for the time period of April 15 through June 14, is the minimum amount necessary to preserve the natural environment to a reasonable degree, for this reach of the San Miguel River. This is based on the assumption that 325 cfs would preserve 90% of the weighted useable area available to the bluehead sucker and 100% of the weighted useable area available to the flannemouth sucker. BLM and CDOW staff also believe a flow that maintains adequate bluehead and flannemouth sucker habitat should also maintain adequate roundtail chub habitat. The spring/summer flow of 325 cfs was reduced to 170 cfs for the June 15 through July 31 time period because of water availability concerns. The instream flow recommendation of 170 cfs was derived to maximize the existing bluehead and flannemouth sucker habitat available under a declining hydrograph, by maintaining an average depth of 1.0 foot over the measured riffle cross-section. An average depth of 1.0 foot combined with average velocities exceeding 1.3 ft/sec, were determined to be marginally suitable bluehead sucker habitat (see Anderson & Stewart Report – Appendix F).

Because the PHABSIM/RHABSIM data only quantified suitable versus unsuitable hydraulic habitat as a function of discharge, CDOW and BLM staff used the results of the R2CROSS Method to develop the fall/winter instream flow recommendation of 115 cfs. The R2CROSS Method suggests that fall/winter flows should maintain at least 2 of 3 of the identified critical hydraulic criteria. At the Cross Section #1 site, 115 cfs meets 2 of 3 criteria (average depth and velocity) by providing on average, 0.8 feet of depth and velocities well over 1.0 ft/sec. The fall/winter flow recommendation was further reduced to 80 cfs, for the time period of September through February, due to water availability concerns. It should be noted however, that 80 cfs still maintains adequate velocity (approximately 2.5 ft/sec), a wetted perimeter of almost 60% and an average depth of nearly 0.7 feet.

APPENDIX – A

RANGE-WIDE
CONSERVATION AGREEMENT AND STRATEGY FOR
ROUNDTAIL CHUB *Gila robusta*,
BLUEHEAD SUCKER *Catostomus discobolus*,
AND FLANNELMOUTH SUCKER *Catostomus latipinnis*

Prepared for
Colorado River Fish and Wildlife Council

Prepared by
Utah Department of Natural Resources
Division of Wildlife Resources
1594 West North Temple, Suite 2110
P.O. Box 146301
Salt Lake City, Utah 84114-6301
An Equal Opportunity Employer

James F. Karpowitz
Director

Publication Number 06-18
September 2006

TABLE OF CONTENTS

RANGEWIDE CONSERVATION AGREEMENT FOR ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER	3
I. Introduction.....	3
II. Goal.....	3
III. Objectives	3
IV. Other species involved.....	4
V. Involved parties.....	6
VI. Authority	7
VII. Conservation actions	9
VIII. Duration of agreement	13
IX. Policy for evaluation of conservation efforts (PECE) compliance	13
X. National Environmental Policy Act (NEPA) compliance	14
XI. Signatories.....	15
RANGEWIDE CONSERVATION STRATEGY FOR ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER	22
XII. Introduction.....	22
XIII. Background.....	23
XIV. Conservation guidelines.....	28
XV. Status assessment of roundtail chub, bluehead sucker, and flannelmouth sucker	39
XVI. Range-wide conservation of roundtail chub, bluehead sucker, and flannelmouth sucker	42
XVII. Conservation actions and adaptive management	43
Literature Cited	48
APPENDIX 1: Standard language required by the state of Arizona	59

RANGEWIDE CONSERVATION AGREEMENT FOR ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER

I. INTRODUCTION

This Conservation Agreement (Agreement) has been developed to expedite implementation of conservation measures for roundtail chub (*Gila robusta*), bluehead sucker (*Catostomus discobolus*), and flannemouth sucker (*Catostomus latipinnis*), hereinafter referred to as the three species, throughout their respective ranges as a collaborative and cooperative effort among resource agencies. Threats that warrant the three species being listed as sensitive by state and federal agencies and that might lead to listing by the U.S. Fish and Wildlife Service as threatened or endangered under the Endangered Species Act of 1973, as amended (ESA), should be minimized through implementation of this Agreement. Additional state, federal, and tribal partners in this effort are welcomed, and such participation (as signatories or otherwise) is hereby solicited.

II. GOAL

The goal of this agreement is to ensure the persistence of roundtail chub, bluehead sucker, and flannemouth sucker populations throughout their ranges.

III. OBJECTIVES

The individual state's signatory to this document will develop conservation and management plans for any or all of the three species that occur naturally within their state. Any future signatories may also choose to develop individual conservation and management plans, or to integrate their efforts with existing plans. The individual signatories agree to develop information and conduct actions to support the following objectives:

- Develop and finalize a conservation and management strategy (Strategy) acceptable to all signatories that will provide goals, objectives and conservation actions to serve as

consistent guidelines and direction for the development and implementation of individual state wildlife management plans for these three fish species.

- Establish and/or maintain roundtail chub, flannemouth sucker and bluehead sucker populations sufficient to ensure persistence of each species within their ranges.
 - 1) Establish measureable criteria to evaluate the number of populations required to maintain the three species throughout their respective ranges.
 - 2) Establish measureable criteria to evaluate the number of individuals required within each population to maintain the three species throughout their respective ranges.
- Establish and/or maintain sufficient connectivity between populations so that viable metapopulations are established and/or maintained.
- As feasible, identify, significantly reduce and/or eliminate threats to the persistence of roundtail chub, bluehead sucker, and flannemouth sucker that: 1) may warrant or maintain their listing as a sensitive species by state and federal agencies, and 2) may warrant their listing as a threatened or endangered species under the ESA.

IV. OTHER SPECIES INVOLVED

This Agreement is primarily designed to ensure the persistence of roundtail chub, bluehead sucker, and flannemouth sucker within their respective distributions. This will be achieved through conservation actions to protect and enhance these species and their habitats. Although these actions will be designed to benefit the three species, they may also contribute to the conservation of other native species with similar distributions.

Bonytail (*Gila elegans*), Colorado pikeminnow (*Ptychocheilus lucius*), humpback chub (*Gila cypha*), and razorback sucker (*Xyrauchen texanus*) are currently listed as endangered under the ESA. In the Upper Colorado River Basin, recovery of one or more of these species has been undertaken by the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin and the San Juan River Basin Recovery Implementation Program. In the Lower Colorado River Basin, the Grand Canyon Monitoring and Research Center and the Lower

Colorado River Multi-Species Conservation Plan have committed to recovery actions for these species. Conservation actions for native fish in the Virgin River Basin are occurring under the direction of the Virgin River Resource Management and Recovery Program in Utah and the Lower Virgin River Recovery Implementation Team in Nevada and Arizona. Fish managed under these programs include the federally endangered woundfin (*Plagopterus argentissimus*) and Virgin River chub (*Gila seminuda*), as well as the Virgin spinedace (*Lepidomeda mollispinis mollispinis*), desert sucker (*Catostomus clarkii*), and flannelmouth sucker. Virgin spinedace is the subject species of a conservation agreement and is listed as a “conservation species” in Utah; it is also listed as “protected” in Nevada. The programs described above focus primarily on mainstem rivers where, in some cases, the three species spend parts of their life cycles.

Although the three species are also found in tributary streams, conservation actions in these habitats have received less emphasis to date. Such actions are, therefore, likely to be the focus of state conservation and management plans developed as part of this Agreement. Any conservation actions implemented through existing recovery programs and/or this Agreement may benefit both the endangered fishes mentioned as well as the three species. The signatories will commit to implement conservation actions under this Agreement and Strategy that neither conflict with nor replicate any conservation actions that have been implemented, are being implemented, or will be implemented under any existing recovery program or conservation agreement.

Additionally, the Agreement may reduce threats to several native species that are not currently listed as threatened or endangered under the ESA, and thereby preclude the need for listing or re-listing in the future. Some of these native species include speckled dace (*Rhinichthys osculus*), Gila chub (*Gila intermedia*), headwater chub (*Gila nigra*), mountain sucker (*Catostomus platyrhynchus*), Zuni bluehead sucker (*Catostomus discobolus yarrowi*), Bonneville cutthroat trout (*Oncorhynchus clarkii utah*), Colorado River cutthroat trout (*Oncorhynchus clarkii pleuriticus*), Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*), mottled sculpin (*Cottus bairdi*), Paiute sculpin (*Cottus beldingi*), northern leopard frog (*Rana pipiens*), relict leopard frog (*Rana onca*), boreal toad (*Bufo boreas boreas*), Great Basin spadefoot (*Spea intermontana*), Great Plains toad (*Bufo cognatus*), New Mexico spadefoot (*Spea*

multiplicata), red-spotted toad (*Bufo punctatus*), Woodhouse toad (*Bufo woodhousei*), canyon treefrog (*Hyla arenicolor*), and western chorus frog (*Pseudacris triseriata*).

V. INVOLVED PARTIES

The following state agencies are committed to work cooperatively to conserve the roundtail chub, bluehead sucker, and flannelmouth sucker throughout their respective ranges, and have further determined that a consistent approach, as described in this Agreement, is most efficient for conserving the three species. The state agencies signatory to this document are:

Arizona Game and Fish Department

Colorado Division of Wildlife

Nevada Department of Wildlife

New Mexico Department of Game and Fish

Utah Division of Wildlife Resources

Wyoming Game and Fish Department

Coordinated participation by state wildlife agencies helps institutionalize range-wide conservation of the three fish species, but federal and tribal partners are being encouraged to participate, as well. The participation of all resource managers in the areas where these species are found is important for the long-term survival of the three species. Some language in this Agreement has been included in anticipation of eventual federal and tribal participation. Any edits proposed by potential conservation partners that will allow them to sign this Agreement and participate in conservation actions will be carefully considered and will only be incorporated with the consensus of the existing signatories. This Agreement may be amended at any time to include additional signatories. An entity requesting inclusion as a signatory shall submit its request to the Council in the form of a document defining its proposed responsibilities pursuant to this Agreement.

VI. AUTHORITY

- The signatory parties hereto enter into this Conservation Agreement and the proposed Conservation Strategy under Federal and State Law, as applicable. Each species' conservation status is designated by state wildlife authorities according to the following table (updated from Bezzerides and Bestgen 2002):

Species	State	Status
Bluehead sucker	Utah	Species of Concern
	Wyoming	Special Concern
Flannelmouth sucker	Colorado, Wyoming	Special Concern
	Utah	Species of Concern
Roundtail chub	New Mexico	Endangered
	Utah	Species of Concern
	Arizona, Colorado, Wyoming	Special Concern

- The signatory parties further note that this Agreement is entered into to establish and maintain an adequate and active program for the conservation of the above listed species.
- The signatory parties recognize that each state has the responsibility and authority to develop a conservation and management plan consistent with the goal and objectives of this Agreement. The purpose of these documents will be to describe

specific tasks to be completed toward achieving the goal and objectives of this Agreement.

- All parties to this Agreement recognize that they each have specific statutory responsibilities, particularly with respect to the management and conservation of these fish, their habitat and the management, development and allocation of water resources. Nothing in this Agreement or the proposed companion Strategy to be developed pursuant to this Agreement is intended to abrogate any of the parties' respective responsibilities.
- This Agreement is subject to and is intended to be consistent with all applicable Federal and State laws and interstate compacts (To this end, the State of Arizona has attached appendix 1.)
- The state of Wyoming and the Commission do not waive sovereign immunity by entering into this Agreement, and specifically retain immunity and all defenses available to them as sovereigns pursuant to Wyoming Statute 1-39-104(a) and all other state law.
- This instrument in no way restricts the parties involved from participating in similar activities with other public or private agencies, organizations or individuals.
- Revisions to this Agreement will be made only with approval of all signatories.
- This Agreement may be executed in several parts, each of which shall be an original, and which collectively shall constitute the same Agreement.

VII. CONSERVATION ACTIONS

The signatories will review and document existing and ongoing programmatic actions that benefit the three species. As signatories develop their individual management plans for conservation of the three species, each signatory may include but is not limited by or obligated to incorporate the following conservation actions:

- 1) Conduct status assessment of roundtail chub, bluehead sucker, and flannelmouth sucker.
- 2) Establish and maintain a database of past, present, and future information on roundtail chub, bluehead sucker, and flannelmouth sucker.
- 3) Determine roundtail chub, bluehead sucker, and flannelmouth sucker population demographics, life history, habitat requirements, and conservation needs.
- 4) Genetically and morphologically characterize populations of roundtail chub, bluehead sucker, and flannelmouth sucker.
- 5) Increase roundtail chub, bluehead sucker, and flannelmouth sucker populations to accelerate progress toward attaining population objectives for respective species.
- 6) Enhance and maintain habitat for roundtail chub, bluehead sucker, and flannelmouth sucker.
- 7) Control (as feasible and where possible) threats posed by nonnative species that compete with, prey upon, or hybridize with roundtail chub, bluehead sucker, and flannelmouth sucker.
- 8) Expand roundtail chub, bluehead sucker, and flannelmouth sucker population distributions through transplant activities or reintroduction to historic range, if warranted.
- 9) Establish and implement qualitative and quantitative long-term population and habitat monitoring programs for roundtail chub, bluehead sucker, and flannelmouth sucker.
- 10) Implement an outreach program (e.g., development of partnerships, information and education activities) regarding conservation and management of roundtail chub, bluehead sucker, and flannelmouth sucker.

Coordinating Conservation Activities

- Administration of the Agreement will be conducted by a range-wide Coordination Team. The team will consist of a designated representative from each signatory to this Agreement and may include technical and legal advisors and other members as deemed necessary by the signatories.
- As a first order of business, the chair of the Coordination Team will be selected from signatory state wildlife agency participants. Leadership will be reconsidered annually, and any member may be selected as Coordination Team Leader with a vote of the majority of the team. The chair will serve no more than two consecutive one-year terms.
- Authority of the Coordination Team will be limited to making recommendations to participating resource management agencies to address status, threats and conservation of roundtail chub, bluehead sucker, and flannelmouth sucker.
- The Coordination Team will meet at least once annually in October or November to develop range-wide priorities, review the annual conservation work plans developed by each agency, review conservation accomplishments resulting from implementation of conservation work plans, coordinate tasks and resources to most effectively implement the work plans, and review and revise the Strategy and states' conservation and management plans as required. They will report on progress and effectiveness of implementing the conservation and management strategies and plans. The Coordination Team will decide the annual meeting date and location.
- Coordination Team meetings will be open to the public. Meeting decision summaries and annual progress reports will be distributed to the Coordination Team and the signatories. Other interested parties may obtain minutes and progress reports upon request.

Implementing Conservation Schedule

- Development of the range-wide Conservation Strategy and states' conservation and management plans will begin no later than March 2004 and be completed no later than December 2004. A 10-year period will be necessary to attain sufficient progress toward objectives outlined in this Agreement, the range-wide Strategy, and the state plans, but the time required to complete conservation actions may be revised with consensus of the signatories.
- Conservation actions will be scheduled and reviewed on an annual basis by the signatories based on recommendations from the Coordination Team. Activities that will be conducted during the first three to five years of implementation will be identified in annual work plans within the states' conservation and management plans. The Strategy and states' conservation and management plans will be flexible documents and will be revised through adaptive management, incorporating new information as it becomes available.
- The state wildlife agency that has the Coordination Team Leader responsibility will coordinate team review of conservation activities conducted by participants of this Agreement to determine if all actions are in accordance with the Strategy and state conservation and management plans, and the annual schedule.
- Following a 10-year evaluation, the Agreement, Strategy, and associated states' conservation and management plans may be renewed.

Funding Conservation Actions

- Expenditures to implement this Agreement and Strategy will be identified in states' conservation and management strategies and are contingent upon availability of funding.
- Implementation funding will be provided by a variety of sources. Federal, state, and local sources will need to provide or secure funding to initiate procedures of the Agreement and Strategy, although nothing in this Agreement obligates any agency to any funding responsibilities. To date, various federal and state sources have contributed to

conservation efforts for the three fish species, including development of the Agreement and Strategy.

- Federal sources may include, but are not limited to, U.S. Forest Service, U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, Bureau of Land Management, Land and Water Conservation funds, and the Natural Resource Conservation Service. Nothing in this document commits any of these agencies to funding responsibilities.
- State funding sources may include, but are not limited to, direct appropriation of funds by the legislature, community impact boards, water resources revolving funds, state departments of agriculture, and state resource management agencies. Nothing in this document commits any of these agencies to funding responsibilities.
- Local sources of funding may be provided by water districts, Native American Affiliations, cities and towns, counties, local irrigation companies, and other supporting entities, and may be limited due to factors beyond local control.
- In-kind contributions in the form of personnel, field equipment, supplies, etc., will be provided by participating agencies. In addition, each agency will have specific tasks, responsibilities and proposed actions/commitments related to their in-kind contributions.
- It is understood that all funds expended in accordance with this Agreement are subject to approval by the appropriate local, state or Federal appropriations. This instrument is neither a fiscal nor a funds obligation document. Any endeavor involving reimbursement or contribution of funds between the parties to this instrument will be handled in accordance with applicable laws, regulations, and procedures, including those for government procurement and printing, if applicable. Such endeavors will be outlined in separate agreements (such as memoranda of agreement or collection agreements) that shall be made in writing by representatives of the parties and which shall be independently authorized by appropriate statutory authority. This instrument does not provide such authority. Specifically, this instrument does not establish authority for noncompetitive awards to the cooperator of any contract or other agreement. Any

contract or agreement for training or other services must fully comply with all applicable requirements for competition.

Conservation Progress Assessment.

- A range-wide assessment of progress towards implementing actions identified in this Agreement and each state conservation and management plan will be provided to the signatories by the Coordination Team in the first, fifth and tenth years of the Agreement and every fifth year thereafter as dictated by any extension of this instrument beyond ten years. The Coordination Team will compile the annual assessment from submittals prepared by members of the Coordination Team. Copies of the annual assessment will be provided to the signatories, and to interested parties upon request.

VIII. DURATION OF AGREEMENT

The term of this Agreement shall be for two consecutive five-year periods. The first five-year period will commence on the date all state signatories to this document are completed. Prior to the end of each five-year period, a thorough analysis and review of actions implemented for the three species will be conducted by the Coordination Team. If all signatories agree that sufficient progress has been made toward conservation and management of the roundtail chub, bluehead sucker, and flannelmouth sucker, this Agreement may be extended without additional signatures being required. Any involved party may withdraw from this Agreement on 60 days written notice to the other parties.

IX. POLICY FOR EVALUATION OF CONSERVATION EFFORTS (PECE) COMPLIANCE

Pursuant to the federal Policy for Evaluation of Conservation Efforts (PECE) guidelines, the signatory agencies acknowledge the role of PECE in providing structure and guidance in support of the effective implementation of this conservation program and will address PECE elements within their respective state conservation and management plans. They also acknowledge and support the principle that documented progress toward stable and increased

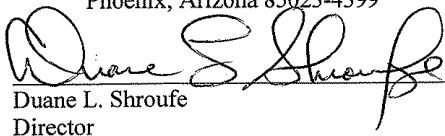
distribution, abundance, and recruitment of populations of the three species constitutes the primary index of effectiveness of this conservation program. Criteria describing population status and trends as well as mitigation of recognized threats comprise the primary basis for evaluation of conservation efforts conducted under this Agreement.

X. NATIONAL ENVIRONMENTAL POLICY ACT (NEPA) COMPLIANCE

The signatories anticipate that any survey, collection, or non-land disturbing research activities conducted through this Agreement will not constitute significant Federal actions under the NEPA, and will be given a categorical exclusion designation, as necessary. However, each signatory agency holds the responsibility to review planned actions for their area of concern to ensure conformance with existing land use plans, and to conduct any necessary NEPA analysis for those actions within their area.

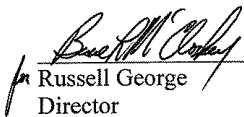
XI. SIGNATORIES

Arizona Game and Fish Department
 2221 W. Greenway Rd.
 Phoenix, Arizona 85023-4399


 Duane L. Shroufe
 Director

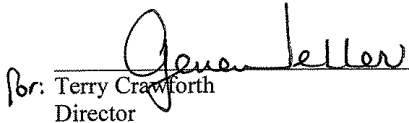
02/23/04
 Date

Colorado Division of Wildlife
 6060 Broadway
 Denver, Colorado 80216


 Russell George
 Director

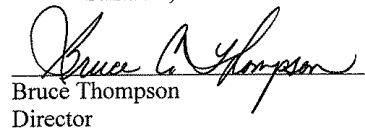
3/23/04
 Date

Nevada Department of Wildlife
 1100 Valley Rd.
 Reno, Nevada 89512


 For: Terry Crawford
 Director

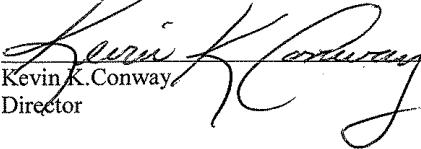
3/5/04
 Date

New Mexico Department of Game and Fish
 P.O. Box 25112
 Santa Fe, New Mexico 87504

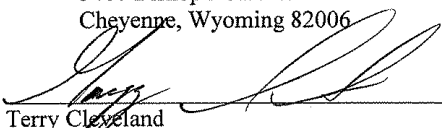

 Bruce Thompson
 Director

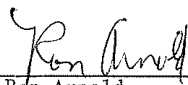
4-15-04
 Date

Utah Division of Wildlife Resources
1594 W. North Temple, Suite 2110
P.O. Box 1456301
Salt Lake City, Utah 84114-6301

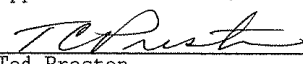

Kevin K. Conway 2/4/04
Director Date

Wyoming Game and Fish Department
5400 Bishop Boulevard
Cheyenne, Wyoming 82006


for Terry Cleveland 3-12-04
Director Date


Ron Arnold 3/11/04
Chief Fiscal Officer Date

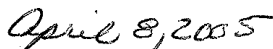
Approval as to form:


Ted Preston 3/11/04
Assistant Attorney General Date

The following signatories support the goals, objectives, and actions of the Conservation Agreement for Roundtail Chub, Bluehead Sucker and Flannelmouth Sucker, version 10.4.4 and agree to support the conservation efforts described.



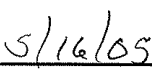
Bureau of Land Management
Wyoming State Office



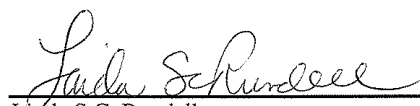
Date

The following signatories support the goals, objectives, and actions of the Conservation Agreement for Roundtail Chub, Bluehead Sucker and Flannelmouth Sucker, version 10.4.4 and agree to support the conservation efforts described.

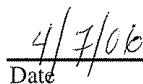

Bureau of Land Management
Utah State Office


Date

The following signatories support the goals, objectives, and actions of the Conservation Agreement for Roundtail Chub, Bluehead Sucker and Flannelmouth Sucker, version 10.4.4 and agree to support the conservation efforts described.



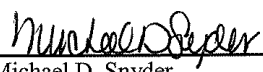
Linda S.C. Rundell
State Director
Bureau of Land Management
New Mexico State Office



Date

The following signatories support the goals, objectives, and actions of the Conservation Agreement for Roundtail Chub, Bluehead Sucker and Flannelmouth Sucker, version 10.4.4 and agree to support the conservation efforts described.

National Park Service
Intermountain Region
12795 W. Alameda Parkway
P.O. Box 25287
Denver, Colorado 80225-0287



Michael D. Snyder
Acting Director

7/5/05

Date

-Signature Page-

This signature page is an appendix to the Range-Wide Conservation Agreement for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker dated 27 January 2004 ("Agreement").

The Jicarilla Apache Nation enters this Agreement pursuant to its inherent authority and pursuant to the Revised Constitution of the Jicarilla Apache Nation, Article XI, Powers of the Tribal Council. Nothing in this Agreement provides a basis for requiring the Jicarilla Apache Nation to comply with state law. Nothing in this Agreement diminishes the jurisdiction of the Jicarilla Apache Nation, including its legislative, regulatory, and judicial jurisdiction, nor does the Agreement waive the sovereign immunity of the Nation.

Jicarilla Apache Nation
Jicarilla Game and Fish Department
P.O. Box 507
Dulce, NM 87528


President Levi Pesata

5/10/06
Date

RANGEWIDE CONSERVATION STRATEGY FOR ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER

XII. INTRODUCTION

This conservation strategy (Strategy) has been developed to provide a framework for the long-term conservation of roundtail chub (Cyprinidae: *Gila robusta*), bluehead sucker (Catostomidae: *Catostomus discobolus*), and flannemouth sucker (Catostomidae: *Catostomus latipinnis*), hereinafter referred to as the three species. Implementation of the Strategy is intended to be a collaborative and cooperative effort among resource agencies to support conservation of the three species throughout their respective ranges. This document provides goals, objectives, and conservation actions to serve as consistent guidelines and direction for the development and implementation of individual state wildlife management plans for the three species. These state conservation and management plans are being developed through an interagency and interested party involvement process. Specific tasks that affect the status of the three species are not reiterated in this document. Rather, we outline the general strategy summarizing the conservation actions to be taken to eliminate or significantly reduce threats and present an overall strategy for the long-term conservation of the three species.

Guidance for specific tasks in state conservation and management plans is summarized in this document. Specific tasks to be completed under the conservation actions set forth in this document will be detailed within respective state conservation and management plans. Likewise, specific tasks that have been completed toward achieving the objectives set forth in this document will also be detailed within the state conservation and management plans. Implementation of these tasks will identify and minimize threats to roundtail chub, bluehead sucker, and flannemouth sucker that: 1) may warrant or maintain their listing as a sensitive species by state and federal agencies, and 2) may warrant their listing as a threatened or endangered species under the Endangered Species Act of 1973, as amended (ESA).

XIII. BACKGROUND

Geographic Setting

The Colorado River Basin (CRB) is home to 22 fish genera, at least 35 fish species and at least 26 endemic fish species, some of which have persisted for over 10 million years (Evermann and Rutter 1895, Miller 1959, Molles 1980, Minckley et al. 1986, Carlson and Muth 1989, Valdez and Carothers 1998, Bezzerides and Bestgen 2002). Geologic isolation, frequent drought and flood, widely ranging temperatures, and high sediment and solute loads in the CRB created a harsh environment that provided a unique setting for the evolution of a distinct group of endemic fishes (Behnke 1980, Ono et al. 1983, Minckley et al. 1986). The CRB is divided into upper and lower basins at Lee's Ferry in north central Arizona, near the Utah border. The San Juan, Colorado, and Green river basins form the upper CRB. In the lower CRB, the Colorado River flows through Grand Canyon National Park and forms state boundaries between Nevada, California and Arizona. Conjoining the Colorado River in Arizona are the Little Colorado and Gila rivers and the Virgin River joins the Colorado in Nevada. The three species occur in both upper and lower portions of the CRB.

The Bonneville Basin (Utah, Nevada, Wyoming, and Idaho) is an endorheic basin, wherein surface water collects from precipitation and upwelling groundwater, but no streams drain out of the basin (Hubbs et al. 1974). Historically, the Bonneville Basin had aquatic affinities with Hudson Bay, and several species stem from northeastern North American progenitors (Sigler and Sigler 1996 and references therein). During geologic history, the Bear River flowed into the Upper Snake River drainage (Columbia River Basin), but currently flows into the Bonneville Basin (Hubbs and Miller 1948; Sigler and Sigler 1996). The bluehead sucker historically occurred in both the CRB and the Bonneville Basin.

Species Descriptions, Life Histories and Hybrids

The three species share several morphological similarities commonly associated with hydrologically variable environments, including: 1) fusiform bodies, 2) leathery skins with embedded scales, and 3) large, often falcate fins. Such morphologic features, combined with

relatively long life spans, may be adaptations to the harsh, unpredictable physical environment of the CRB (Scoppettone 1988, Minckley 1991, Stearns 1993, Bezzerides and Bestgen 2002). Life history characteristics, distribution and abundance have been described for roundtail chub (Bestgen and Propst 1989, Brouder et al. 2000, Voeltz 2002), bluehead sucker (e.g., McAda 1977, Holden and Minckley 1980, McAda and Wydoski 1983, Cavalli 1999 and Bestgen 2000), and flannelmouth sucker (Chart 1987, Douglas and Marsh 1998, McKinney et al. 1999). Bluehead sucker are also discussed in Valdez (1990), Mueller et al. (1998), Brunson and Christopherson (2001), and Jackson (2001).

Roundtail Chub

Roundtail chub utilize slow moving, deep pools for cover and feeding. These fish are found in the mainstem of major rivers and smaller tributary streams. Roundtail chub utilize a variety of substrate types (silt, sand, gravel and rocks) and prefer murky water to clear (Sigler and Sigler 1996, Brouder et al. 2000). Roundtail chub partition habitat use by life stage [adult, juvenile, young-of-year (YOY)].

Juveniles and YOY are found in quiet water near the shore or backwaters with low velocity and frequent pools rather than glides and riffles. Juveniles avoid depths greater than 100 cm and YOY avoid depths greater than 50 cm. Juveniles use instream boulders for cover, while YOY are found in interstices between and under boulders or the slack-water area behind boulders (Brouder et al. 2000).

Adults generally do not frequent vegetation and avoid shallow water cover types (overhanging and shoreline vegetation) (Sigler and Sigler 1996, Brouder et al. 2000). Adults are found in eddies and pools adjacent to strong current and use instream boulders as cover (Sigler and Sigler 1996, Brouder et al., 2000). Adults occupy depths greater than 20 cm and select for velocities less than 20 cm/s. Adults may range 100 m or less over the course of a year, often in search of pool habitats (Siebert 1980; Brouder et al 2000).

Sigler and Sigler (1996) report that roundtail chub mature at five years of age and/or 254 mm to 305 mm in length and that spawning begins in June to early July when water temperatures reach 18.3 °C. However, Peter Cavalli, Wyoming Fish and Game Department, has collected

unpublished data (2004 personal communication) indicating that roundtail chub in Upper Green River drainage lakes may mature at sizes as small as 150 mm in water temperatures of 14.4 °C. Eggs from one female may be fertilized by three to five males over gravel in water up to 9.1 m. A 305 mm female can produce 10,000 eggs, 0.7 mm in diameter. The eggs are pasty white and adhesive, sticking to rocks and other substrate or falling into crevices (Sigler and Sigler 1996).

Roundtail chub are carnivorous, opportunistic feeders. Documented food items include aquatic and terrestrial insects, fish, snails, crustaceans, algae, and occasionally lizards (Sigler and Sigler 1996, Osmundson 1999, Bestgen 2000, Brouder 2001).

Bluehead Sucker

Bluehead sucker tend to utilize swifter velocity, higher gradient streams than those occupied by either flannemouth sucker or roundtail chub. These fish are found in warm to cool streams (20 °C) with rocky substrates (Sigler and Sigler 1996, Bestgen 2000). Bluehead sucker do not do well in impoundments (Sigler and Sigler 1996, Bezzerides and Bestgen 2002). Bluehead sucker partition habitat use by life stage [adult, juvenile, young-of-year (YOY)]. Larval fish inhabit near-shore, low velocity habitats (Childs et al. 1998). As they age, they move to deeper habitats further away from shore, and with more cover (Childs et al. 1998).

Larval and early-juvenile bluehead sucker eat mostly invertebrates (Childs et al. 1998). At later life-stages, they are more opportunistic omnivores, consuming algae, detritus, plant debris, and occasionally aquatic invertebrates (Sigler and Sigler 1996, Osmundson 1999, and Bestgen 2000). This species feeds in riffles or deep rocky pools (McAda 1977, Sigler and Sigler 1996).

Bluehead sucker mature at two years of age and/or at 127 to 179 mm in length. Spawning occurs in shallow areas when water temperatures reach 15.6 °C. Time of spawning varies by elevation, i.e., spring and early summer at low elevations and warm water temperatures, and mid- to late summer at higher elevations and cooler temperatures (Sigler and Sigler 1996). Fecundity is related to length, body weight (Holden 1973), and water temperature (McAda 1977). A 38 to 44 cm female may produce over 20,000 eggs (Andreason 1973). Eggs

hatch in seven days at water temperatures of 18 to 21 °C (Holden 1973). Bluehead sucker, when disturbed during spawning, will compress to the bottom of the stream and can be captured by hand (Sigler and Sigler 1996). After hatching, larval fish drift downstream and seek out near-shore, slow-velocity habitats (Robinson et al. 1998).

Flannemouth Sucker

Flannemouth sucker reside in mainstem and tributary streams. Elements of flannemouth habitat include 0.9 to 6.1 m deep murky pools with little to no vegetation, and deep runs and riffles (McAda 1977, Sigler and Sigler 1996, Bezzerides and Bestgen 2002). Substrates utilized consist of gravel, rock, sand, or mud (McAda 1977, Sigler and Sigler 1996).

Flannemouth sucker partition habitat use by life stage, with young fish occupying quiet, shallow riffles and near-shore eddies (Childs et al. 1998), and adults occupying deep riffles and runs. Many authors report that flannemouth sucker do not prosper in impoundments (McAda 1977, Sigler and Sigler 1996, Bezzerides and Bestgen 2002); however, some lakes in the Upper Green River drainage in Wyoming supported large flannemouth sucker populations historically (Baxter and Stone 1995; P. Cavalli, Wyoming Game and Fish Department, 2004 personal communication). Flannemouth sucker are opportunistic, benthic omnivores consuming algae, detritus, plant debris, and aquatic invertebrates (McAda 1977, Sigler and Sigler 1996, Osmundson 1999, Bezzerides and Bestgen 2002). Food consumed depends on availability, season, and the individual's age class (McAda 1977, Sigler and Sigler 1996). Larval and early juveniles consume mostly invertebrates (Childs et al. 1998).

Flannemouth suckers mature at four to five years of age. Males mature earliest (McAda 1977, Sigler and Sigler 1996). Females ripen at water temperatures of 10 °C, whereas males ripen earlier in the spring (6.1 to 6.7 °C) and remain fertile for longer periods than females (McAda 1977, Sigler and Sigler 1996). Seasonal migrations are made in the spring to suitable spawning habitat (Suttkus and Clemmer 1979, Sigler and Sigler 1996). McKinney et al. (1999; see also Chart 1987, Chart and Bergersen 1987, Bergersen 1992) documented long-range movements (ca. 98-231 km) among adult and sub-adult fish, although the roles these movements play in life history are unclear and need further investigation. Obstructions to movements such

as dams may also be an important consideration in the conservation of flannelmouth suckers. Flannelmouth suckers generally spawn for two to five weeks over gravel. A female will produce 9,000 to 23,000 adhesive, demersal eggs. After fertilization, the eggs sink to the bottom of the stream and attach to substrate or drift between crevices (Sigler and Sigler 1996). After hatching, larvae drift downstream and seek out near-shore, low-velocity areas (Robinson et al. 1998).

Hybrids

Potential hybridization among *Gila* species in the CRB has caused management agencies to carefully consider their conservation actions. In Utah, hybridization between humpback chub (*Gila cypha*) and bonytail (*G. elegans*) in Desolation and Gray Canyons of the Green River has been postulated by many observers. The Virgin River chub (*Gila seminuda*) found in the Muddy River has been historically treated as a subspecies of roundtail chub (*G. robusta*) and is thought to be a hybrid between the bonytail (*G. elegans*) and the Colorado roundtail chub (*G. r. robusta*; Maddux et al. 1995, Sigler and Sigler 1996 and references therein). In 1993, taxonomic revisions were accepted, and the Virgin River chub was asserted species status as *G. seminuda* (DeMarais et al. 1992, Maddux et al. 1995). The Virgin River chub is currently listed as endangered under the ESA.

Whether biologists and agencies recognize two species, two species and a hybrid form, three species, or some other combination has implications for how the fish are managed. Because roundtail chub are congeners with humpback chub and bonytail, the potential for hybridization with roundtail exists, although this has not been as well documented as the hybridization between humpback chub and bonytail (e.g., Valdez and Clemmer 1982, Kaeding et al. 1990, Dowling and DeMarais 1993, Douglas and Marsh 1998). Valdez and Clemmer (1982) have suggested that hybridization is a negative result of dramatic environmental changes, while Dowling and DeMarais (1993) and McElroy and Douglas (1995) suggest that hybridization among these species has occurred continually over geologic time, providing offspring with additional genetic variability. Barriers to hybridization among *Gila* species suggest that it is a paraphyletic genus (Coburn and Cavender 1992 and references therein). Putative roundtail chub in the Gila River drainage of New Mexico and Arizona was recently divided into three species,

G. robusta, *G. intermedia*, and *G. nigra* (Minckley and DeMarais 2000). Additional investigation of these relationships and resulting offspring is required and results may affect future conservation and management actions for roundtail chub and other *Gila* species. Hybridization between bluehead sucker and Rio Grande sucker (*C. plebius*) is thought to have produced the Zuni bluehead sucker (*C.d. yarrowi*), a unique subspecies found mainly in Rio Nutria, NM.

Douglas and Douglas (2003) report that both indigenous bluehead and flannelmouth sucker currently hybridize with invasive white sucker (*Catostomus commersoni*) in the Little Yampa Canyon region of the Yampa River, Colorado. Two hybrids between flannelmouth and bluehead sucker were also found in their study, which is extremely rare elsewhere in the CRB. Douglas and Douglas (2003) suggest backcrossing of fertile indigenous and invasive sucker hybrids as a mechanism that perpetuates introgressed genes. They also speculate that the species boundary between flannelmouth and bluehead suckers could be compromised as a result.

XIV. CONSERVATION GUIDELINES

This section presents a generalized discussion on conservation topics relevant to the conservation of the three fish species. Intended as a guide for development of state conservation plans, it does not specifically outline minimum requirements for development of such plans. Rather, the signatories recognize that the priority of issues discussed in this section may vary widely from state to state and that the feasibility of resolving management implications discussed herein is situation- and species-specific. Furthermore, it is likely that conservation issues discussed in these sections will frequently be interrelated. For example, genetic concerns will likely be addressed in concert with metapopulation, population viability, and nonnative fish issues. Likewise, nonnative fish control issues may impact habitat management, and in some instances, hybridization issues (e.g., occurrence of white sucker in the upper CRB), and so on. It is therefore desirable that state managers identify interrelationships between conservation issues and formulate their state plans accordingly.

Habitat Maintenance and Protection

Habitat is an important component of metapopulation and species survival. Loss of available habitat may lead to the loss of individuals or populations that in turn may cause loss of metapopulation dynamics. Important physical habitat characteristics may include (but are not limited to) substrate, instream habitat complexity, and flow regimes. Chemical characteristics may include (but are not limited to) instream pH, temperature, specific conductance, suspended solids, dissolved oxygen, major ions (e.g., carbonate), nutrients, and trace elements. If needed, the signatories will develop habitat improvement actions to support individual populations and metapopulation dynamics. Rigorous standards for habitat protection can be incorporated into state fishery and land use plans. Current guidelines exist for many agencies that can be incorporated into these efforts, including (but not limited to) Best Management Practices or other state water quality standards, Forest Plan Standards and Guidelines, National Park Service Natural Resources Management Guidelines (DO-77), and recommendations from related broad-scale assessments. Properly Functioning Condition (PFC) protocols are found in Bureau of Land Management publication TR 1737-15 (1998) “Riparian Area Management, a User Guide to Assessing Proper Functioning Condition and Supporting Science for Lotic Areas.”

One of the most dramatic anthropogenic changes imposed on the CRB and Bonneville basins is alteration of natural flow regimes. Instream flow and habitat-related programs administered through existing recovery and conservation programs in upper and lower Colorado River basins can provide guidance for development of similar programs for the three species. Studies conducted by the Upper Colorado River Basin Endangered Fish Recovery Program can aid in identifying habitat requirements for main channel three species populations and select tributary populations (e.g., Chart and Lentsch 1999, Trammel et al. 1999, Muth et al. 2000, Osmundson 2001, Tyus and Saunders 2001, McAda 2003). Other examples of habitat management for tributary cypriniform populations have been proposed for the Virgin River (Lentsch et al. 1995; Lentsch et al. 2002).

Habitat availability for flannelmouth and bluehead sucker as a function of stream discharge was recently identified in Anderson and Stewart (2003). The goal of this study was to

derive biologically based instream flow recommendations for non-endangered native fish, which makes the study germane as a three species conservation guideline. Habitat quality and quantity were derived by relating output from two-dimensional (2-D) hydraulic models of mesohabitat availability (as a function of discharge) to patterns of fish abundance over a three-year period among three different systems (Dolores, Yampa, and Colorado rivers). The 2-D approach is advantageous over previous instream flow methods because it is not dependent on microhabitat suitability curves (and their attendant assumptions) for prediction of habitat availability. The higher level of spatial resolution attained by the 2-D allows for greater accuracy in habitat quantification. The 2-D approach as utilized in Anderson and Stewart (2003) is also advantageous because output is interpreted alongside relevant biological information such as non-native fish abundance and native fish size structure in the modeled stream reaches.

Nonnative fish control

Impacts of nonnative fish on native fish fauna of the Southwestern U.S. are dramatic. Of 52 species of fish currently found in the upper CRB, only 13 are native (six of these are endangered; U.S. Fish and Wildlife Service [FWS] 2003b). Native fish populations in the lower CRB have been similarly impacted by establishment of nonnative fish populations (Minckley et al. 2003). Direct and indirect impacts of nonnative fish on native fish fauna can be measured as changes in the density, distribution, growth characteristics, condition or behavior of both individual native fish and native fish populations (Taylor et al. 1984; Hawkins and Nesler 1991). These changes result from altered trophic relationships (predation, competition for food), spatial interactions (competition for habitat), habitat alteration, hybridization, and/or disease or parasite introductions.

All major recovery plans in the Southwestern U.S., including those of the San Juan River Basin Recovery Implementation Program (SJRIIP; SJRIIP, 1995), the Upper Colorado River Endangered Fish Recovery Program (UCREFRP; FWS 2003b), the June Sucker Recovery Implementation Program (JSRIIP; FWS 1999), and the Virgin River Resource Management and Recovery Program (FWS 1995), identify control of nonnative fish species to alleviate competition with and/or predation on rare fishes as a necessary management action. Due to extensive use by the three species of lower-order streams throughout their range, however, states

may have to identify HUC-specific control measures for nonnative fish. Guidelines for development of nonnative fish management actions (Hawkins and Nesler 1991; Tyus and Saunders 1996; Lenstch et al. 1996; SWCA Inc. 2002) include:

- 1) Assessment of impacts of nonnative fish on native fish populations, including problem species and probable impact mechanisms.
- 2) Identification of spatial extent of impacted populations and potential nonnative source systems; prioritization of areas by severity and cost/benefit ratios.
- 3) Development of coordinated nonnative fish control strategies; identification of potential sport fishing conflicts.
- 4) Identification and use of effective nonnative control methods.
- 5) Development of programs to monitor results of nonnative control measures.
- 6) Assurance that I & E and outreach programs are in place to communicate intentions and findings to the public.

Tyus and Saunders (1996) identified three basic strategies for nonnative fish control in the upper CRB:

- 1) Prevention. Nonnative fish are prevented from entering a system by physical barriers or other control structures, removed directly from potential source water bodies, or prevented from being stocked through regulatory mechanisms.
- 2) Removal. Nonnative fish are removed directly from a system or forced out through creation of unfavorable habitat conditions.
- 3) Exclusion. Nonnative fish are excluded from preying upon or otherwise interfering with native fish through active management, particularly in nursery areas including, but not limited to, installation of barriers during rearing periods.

Strategies may be applied at the basin-wide level or applied to high priority areas within a specific body of water such as nursery or reproductive habitats where native offspring are most vulnerable to predation. Strategies for control of nonnative fish should be developed at the state level. Evaluations of state nonnative fish stocking policies can be found for Colorado (Upper Colorado River Endangered Fish Recovery Program 2002; Martinez et al., in review) and Utah (Holden et al. 1996; Upper Colorado River Endangered Fish Recovery Program 2002). Potential conflicts of nonnative fish control actions with sport fishing management may be difficult to resolve, and may require the development of regional coordinated sport and native fish management strategies. Such strategies often include sufficient monitoring to demonstrate results of nonnative fish control efforts. Outreach programs have been utilized to communicate these results to the public.

Nonnative fish control techniques, specifically applications to southwestern fisheries, have been identified by Lentsch et al. (1996) and SWCA Inc. (2002). Control techniques are categorized as mechanical (angling, commercial fishing, electrofishing, netting), chemical (rotenone, antimycin), biological (introduce predator/competitor, genetically altered individuals, or disease), physical (barriers, screens), physicochemical (habitat modification), or some combination of these. Based on a survey of available literature, SWCA Inc. (2002) identified use of a combination of techniques as the most effective means of controlling nonnative fish abundance. All approaches require a prior knowledge of the target species life history and the physical characteristics of the system they reside in. Documentation of a positive native fish population response to control efforts poses a formidable challenge to managers, but one that ultimately must be addressed.

Population Viability

One of the most fundamental and difficult questions that a wildlife conservation program can address is whether a wild population of animals will persist into the future. Evaluation of the viability of populations may consider available information from the past, the current condition of the species, and the degree of known threats. Population viability analysis also considers what is known about population genetics and demographics, e.g. the probability that very small populations will inbreed and be lost.

This Strategy does not prescribe any one specific method of population viability analysis. Instead, all state signatories agree to develop their own manner of estimating population viability, recognizing the importance of overlapping methods where feasible and applicable. In addition, it is recognized that additional information will be acquired over the course of the Agreement and will thus be adaptive in their approach for estimating population viability. The Strategy identifies the following population viability factors that may be considered, although other appropriate factors may be added to this list in the future:

1. Known and potential threats
2. Available habitat(s)
3. Habitat stability
4. Genetic stability
5. Metapopulation connectivity and stability
6. Reproductive opportunity and potential, including recruitment into the effective population
7. Potential to expand population sizes and distribution

Population viability is a function of population demographics (size and age structure), population redundancy (number and distribution), habitat carrying capacity (resource limitations), and genetic stability (inbreeding and genetic diversity; Franklin 1980; Soulé 1980; Shaffer 1987; Allen et al. 1992). Viable, self-sustaining populations are characterized as having a negligible chance of extinction over century time scales, are large enough to be sustained through historical environmental variation, are large enough to maintain genetic diversity, and maintain positive recruitment near carrying capacity. Establishment of functioning metapopulations (see next section) can fulfill several of these criteria, including stabilization of population dynamics (Wilcox and Murphy 1985, Hanski and Gilpin 1991), increasing range-wide genetic heterogeneity (Simberloff and Abele 1976), and decreasing probability of population losses through environmental and demographic stochasticity (Roff 1974, Wilcox and Murphy 1985).

Metapopulation Dynamics and Function

A metapopulation consists of a series of populations existing in discrete habitat patches linked by migration corridors. Although individual populations should be managed and protected, some degree of interconnectedness among populations (i.e., a metapopulation) is needed to maintain genetic exchange and stabilize population dynamics (Meffe 1986; Wilcox and Murphy 1985, Hanski and Gilpin 1991). Metapopulations stabilize local population dynamics by: 1) allowing genetic exchange among local populations and thereby increasing genetic heterogeneity (Simberloff and Abele 1976); 2) decreasing vulnerability of populations to losses through environmental and demographic stochasticity (Roff 1974, Wilcox and Murphy 1985); and 3) increasing resistance of populations to changes in deterministic variables (birth, survival and death rates; Connell and Sousa 1983; Rieman and McIntyre 1993). Metapopulation dynamics and persistence depend on species life history, connectivity between habitat patches, and the amount and rate of change in available habitat. A metapopulation may thrive as long as immigration (or recruitment) is greater than extinction (or mortality), the amount of habitat remains the same or increases, and populations remain connected. Metapopulations facilitate exchange of genetic material among populations. If migration is prevented over time, populations that were once connected can follow different evolutionary paths for adaptation to local environments. Migrating breeders within a metapopulation help slow or prevent inbreeding depression by maintaining genetic diversity and contributing genetic material not represented in local populations.

Metapopulations can stabilize populations throughout their range. Stream reaches depopulated following stochastic or anthropogenic events may re-populate from connecting, neighboring populations as long as sufficient migration corridors are maintained. However, diversions, dams, and dewatering within stream systems decrease the amount of connectivity between populations of aquatic species. Corridors require sufficient flows, at least during migration periods, and cannot exceed maximum migration distances. Diversions and dams eliminate connectivity by blocking fish migration routes. Dewatering a stream reach may also temporally reduce the amount of available habitat within a stream and, depending on life history, impact survival of the species in question. Potential management actions may include improving

and protecting migration corridors that provide connectivity between historically connected populations, moving fish beyond impassable barriers to simulate historical migration patterns, and improving, protecting, and expanding available flows and habitat. Metapopulation issues (together with conservation genetics) involving interstate waters should be addressed through coordination among the bordering states and with cooperative work between federal land management agencies and state agencies.

Conservation Genetics

Genetic issues vary throughout the range of the three species. Rather than identify issues here for each state, state conservation plans should contain their own prioritization conservation genetics issues among the three species. However, the general goals of range-wide conservation genetics should be to preserve available genetic diversity, including identifying and preserving genetically distinct populations as well as those providing redundancy of specific genetic material across the species' range. Genetically distinct populations should receive special management consideration. Effective conservation and management of the three fish species requires knowledge of the levels of genetic diversity that exist both within and among populations (Chambers and Bayless 1983; Hamrick 1983; Meffe 1986; Soulé 1986, Hallerman 2003). Small, fragmented populations are at greatest risk of genetic diversity loss due to increased frequency of rare, deleterious alleles *within* the population and consequent decreased ability to respond to environmental changes (Lande 1988). *Among* population variation indicates a historical lack of gene flow and subsequently the opportunity for local adaptation, although rapid outbreeding among such groups can cause reductions in relative fitness of offspring. Aquatic systems in the CRB and the Bonneville Basin have undergone large-scale anthropogenic changes in the last 150 years, including alteration of natural hydrology, temperature regime, sediment loads and community composition through introductions of exotic species. System fragmentation, species range contraction, and local declines in population size resulting from these changes can impact genetic diversity within and among populations. Protection of genetic diversity can be accomplished through protection of existing populations, maintenance or re-establishment of migration corridors, transplants of fish from other areas (augmenting existing populations or re-establishing lost populations), or other means.

A first step toward a conservation and management program is to identify genetically distinct populations or management units within individual state boundaries and among interstate waters. As the signatories to this Strategy assess the status of the three species, genetic diversity of the populations should be evaluated, including review of available data and literature on genetic structuring and identification of necessary morphologic and molecular data needed to make management decisions regarding the species' biological requirements. Genetic (and probably metapopulation-related) issues involving interstate waters should be addressed as such, and coordination among the bordering states is necessary to resolve these issues.

No single approach is best to determine the levels of differentiation within and among populations and it is best to incorporate a variety of different kinds of information for each population. For example, geographic, molecular and morphological or meristic data can all provide important quantitative information on population differences (Chambers 1980; Vrijenhoek et al. 1985; Meffe 1986). Conservation and management actions for divergent populations of the three species may be based on the results of these analyses in conjunction with other fish population assessment tools, such as population estimates, population viability analysis, life history information, distributions, and habitat analysis. From a genetic perspective, identification and designation of populations may include 1) analysis of nuclear DNA markers, 2) mitochondrial DNA analysis, and 3) meristic and morphologic traits. The signatories will work together as appropriate to ensure that genetic techniques and tools can be used during range-wide assessments.

The signatories will review available peer-reviewed and gray literature sources for data regarding genetic structuring of the three species. In the absence of information to the contrary, populations from neighboring hydrologic units (taken from the U.S.G.S. Hydrologic Unit Code, or HUCs) will be assumed more similar to each other and more distinct from populations of the same species distributed farther away. Populations within the same HUC are presumably more similar to each other than to populations of the same species from neighboring HUCs. These assumptions and any relevant management recommendations will be evaluated as additional data become available. Additional data can be used to help identify the most genetically unique populations as well as those HUCs where the greatest diversity among populations of one or

more of the three species is distributed. Unless data to the contrary are developed, populations with greater proportions of heterozygotes will be designated more diverse and resilient to environmental change than those of greater proportions of homozygotes (Reed and Frankham 2003, Hallerman 2003).

Hybrids

Fitness is defined herein as a species' ability to thrive and reproduce in its environment and respond to environmental change. While the ability to respond to environmental change is often impossible to predict, geneticists generally agree that genetically diverse populations exhibit high degrees of fitness. Conversely, populations with less diversity are less fit as they have fewer alleles that may be expressed in response to changing environmental conditions (Reed and Frankham 2003). There are examples of detrimental hybridization whereby fitness of either species does not increase or decline. In fishes, high fecundity and external fertilization increase the probability of hybridization, which may have given rise to some of the species we recognize today. The ability to hybridize does not always lead to the loss of one or more species. Persistent, long-term hybridization among species has been documented between flannelmouth suckers and razorback suckers (Buth et al. 1987). The observation that many of the various *Gila* species native to the CRB share alleles suggests ongoing hybridization between roundtail chub and other chubs (DeMarais et al. 1992, Dowling and DeMarais 1993). By incorporating additional non-deleterious alleles, hybridization may confer additional fitness or increased ability to respond to environmental stressors. As available habitat has been reduced from historic times, especially due to impoundment and reduced flows, the likelihood of hybridization among closely related species has increased.

There are two documents which could potentially affect the states' conservation and management actions regarding populations comprised partly by hybrids: 1) The Proposed Policy on the Treatment of Intercrosses and Intercross Progeny (Intercross Policy; 61 FR 4709); and 2) The Policy Regarding the Recognition of Distinct Population Segments Under the Endangered Species Act (DPS Policy; 61 FR 4722). Under the non-binding Intercross Policy, the FWS has responsibility for conserving hybrids under ESA (intercrosses) if 1) offspring share traits that characterize the taxon of the listed parent, and 2) offspring more closely resembles the listed

parent's taxon than an entity intermediate between it and the other known or suspected non-listed parental stock. The Intercross Policy proposes the use of the term "intercross" to represent crosses between individuals of varying taxonomic status (species, subspecies, and distinct population segments). Under this proposed policy, populations can contain individuals that represent the protected species and intercrosses between the protected species and another.

While the intercross policy has not been formally adopted, the FWS has scientifically developed intercross policy concepts in completing their 12-month finding for westslope cutthroat trout (WCT; FWS 2003a). They justified inclusion of hybridized fish in their assessment of WCT if such fish conformed morphologically to published taxonomic descriptions. While such fish may have a genetic ancestry derived by up to 20% from other fish species, the FWS concluded that they also possessed the same behavioral and ecological characteristics of genetically pure fish. They stress, however, that additional criteria should be evaluated, including whether the individual is hybridized with a native or introduced fish and the geographic extent of hybridization. Similar to portions of the FWS testimony, Peacock and Kirchoff (2004) recommended that hybridization policies be flexible enough to allow for conservation of hybridized fish, if in fact genetically pure populations are rare. These concepts could have significant influence in the interpretation of genetic and biological data on roundtail chub, which are suspected to hybridize with endangered *Gila* species (*G. elegans*, *G. cypha*) in certain regions of the CRB.

The DPS Policy requires the FWS to consider three elements in decisions regarding the status of a possible DPS: 1) discreteness of the population segment in relation to the remainder of the species to which it belongs; 2) the significance of the population segment to the species to which it belongs, and 3) the population segment's conservation status in relation to ESA standards for listing. The policy recognizes the importance of unique management units to the conservation of the species and that management priorities can vary across a species' range according to the importance of those population segments. Taken together, the Intercross and DPS policies require that conservation actions for the species be completed by compiling standardized information for each population such that the influence of hybridization and other unique characteristics of the population segments can be identified (Lenstch et al. 2000).

Signatories should review the literature available on hybridization and adequacy of existing data to characterize the degree of hybridization and its impact on fitness among the three species. If additional data are required, additional research on this subject should be conducted. Additional research may characterize genetic structure of the populations, quantify the degree of hybridization, and evaluate whether hybridization appears to be decreasing, maintaining or increasing fitness. If hybridization (whether with nonnative or native species) is decreasing fitness, then management actions to reduce deleterious hybridization may be implemented.

XV. STATUS ASSESSMENT OF ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER

Distribution

The roundtail chub, bluehead sucker, and flannelmouth sucker are three of the least-studied fishes native to the CRB and the Bonneville Basin. Available literature suggests that the three species were common to all parts of the CRB until the 1960s (Sigler and Miller 1963, Jordan and Evermann 1869, Minckley 1973). There have been no range-wide distribution or status assessments for any of these three species preceding the current review of Bezzerides and Bestgen (2002), which concludes that distributions of all three fish species have contracted 50%, on average, from their historic distributions.

Roundtail chubs are found in Wyoming in tributaries to the Green River and in several lakes in the upper portion of the basin. Extant, but declining roundtail chub populations in Utah occur in the Escalante and San Rafael rivers; portions of the middle and upper San Juan River and some tributaries; the Colorado River from Moab to Silt, Colorado; the Fremont River; the Green River from the Colorado River confluence upstream to Sand Wash and from Jensen to Echo Park; the White River from the Green River confluence upstream to near Meeker, Colorado (Bezzarides and Bestgen 2002); and the Duchesne River from the Green River confluence upstream to Myton (Brunson 2001). Roundtail chub presently occur in the lower Colorado River basin in Arizona and New Mexico, in tributaries of the Little Colorado River and Bill Williams River, and in the Gila River and tributaries (Voeltz 2002). Lee et al. (1980) also recorded occurrences in northern Mexico, which was anecdotally confirmed by personal communications

in 2001 with S. Contreras-Balderas (Bioconservación A.C., Monterrey, Nuevo Leon) and A. Varela-Romero (Universidad de Sonora, Hermosillo). Fishes formerly considered roundtail chub outside the Colorado River basin in Mexico are now considered a different species, *Gila minacae* (S. Norris, California State University Channel Islands, personal communication 2004).

Although little information exists on distribution of bluehead sucker (but see McAda 1977, Holden and Minckley 1980, and McAda and Wydoski 1983), they historically occurred in large rivers and tributaries in the CRB (including the Colorado, Green, and San Juan river sub-basins), the Bonneville Basin in Utah, the Snake River Basin in Idaho, Nevada, and Utah (Lee et al. 1980; Ryden 2001), and the Little Colorado River Basin in Arizona and New Mexico (Minckley 1973). Bluehead sucker are found in portions of the Bonneville and Snake River Basins in Wyoming (Baxter and Stone 1995) as well mainstem habitats and several tributaries to the Colorado and Green rivers.

Bluehead sucker populations occur in the Escalante, Dirty Devil, and Fremont rivers (Colorado River tributaries) and in the San Rafael, Price, and Duchesne rivers (Green River tributaries); in the Weber and upper Bear River drainages; in the mainstem Green River from the Colorado River confluence upstream to Lodore, Colorado; in the White River from the Green River confluence upstream to near Meeker, Colorado; in the Yampa River from the Green River confluence upstream to Craig, Colorado; in the San Juan River, Utah, New Mexico and Colorado; in the Colorado River from Lake Powell upstream to Kremmling, Colorado; in the Dirty Devil River in Utah; and in the Dolores River from the Colorado River confluence upstream to McPhee Reservoir, Colorado (Holden and Stalnaker 1974; Sigler and Sigler 1996; Bezzerides and Bestgen 2002). Bluehead sucker also occur in the following tributaries to the Colorado River in Grand Canyon: Bright Angel Creek, Little Colorado River (including headwater tributaries Nutrioso Creek, East, West, and South Fork of the Little Colorado River, East Clear Creek, and Chevelon Creek), Clear Creek, Shinumo Creek, Kanab Creek, and Havasu Creek.

Flannelmouth sucker occur above Flaming Gorge Reservoir in the Green River and its tributaries as well as in some naturally occurring lakes in this drainage. Flannelmouth sucker are

currently found in the Escalante and Fremont rivers (Colorado River tributaries), the San Rafael, Price and Duchesne rivers (Green River tributaries); the mainstem San Juan River and tributaries; the Colorado River from Lake Powell upstream to near Glenwood Springs, Colorado; the Gunnison River in Colorado; the Dolores River; the Green River from the Colorado River confluence upstream to Flaming Gorge Reservoir; in the Dirty Devil River in Utah; and the Yampa and White rivers upstream from their confluences with the Green River. Populations of flannelmouth sucker also exist in the main channel Colorado River below Glen Canyon Dam and in the Virgin River. Flannelmouth sucker also occur in the following Grand Canyon tributaries during portions of their life cycle: Paria River, Bright Angel Creek, Kanab Creek, Shinumo Creek, Havasu Creek and the Little Colorado River including Nutrioso Creek and possibly other headwater tributaries (Little Colorado sucker may or may not be genetically distinct from flannelmouth sucker). Flannelmouth sucker are also common below Davis Dam (Mueller and Wydoski 2004) on the lower Colorado River. Although flannelmouth sucker populations usually do not persist in impoundments (Sigler and Sigler 1996; Bezzerides and Bestgen 2002), individuals were recently documented in Lake Havasu and Lake Mead, Lower Colorado River (Mueller and Wydoski 2004, Arizona Game and Fish Department, unpublished).

Status

Available information indicates that roundtail chubs now occupy approximately 45% of their historical range in the CRB. In the upper CRB (New Mexico, Colorado, Utah, and Wyoming), it has been extirpated from approximately 45% of their historical range, including the Price River (Cavalli 1999) and portions of the San Juan River, Gunnison River, and Green River (Bezzerrides and Bestgen 2002). Data on smaller tributary systems are largely unavailable, and population abundance estimates are available only for short, isolated river reaches (Bezzerrides and Bestgen 2002). In the lower CRB, current estimates of roundtail chub distribution are as low as 18% of their former range (Voeltz 2002). A petition to list the lower Colorado River Basin roundtail chub under the ESA was filed in April 2003 and the finding from the Fish and Wildlife Service is expected in 2006. Roundtail chub are listed as a species of concern by the states of Arizona, Utah, Wyoming, and Colorado. The state of New Mexico lists roundtail chub as endangered.

Bluehead suckers presently occupy approximately 50% of their historically occupied range in the CRB. In the upper CRB (Utah, Wyoming, Colorado and New Mexico), bluehead suckers currently occupy approximately 45% of their historical habitat. Recent declines of bluehead suckers have occurred in the White River below Taylor Draw Dam (Utah and Colorado) and in the upper Green River (Holden and Stalnaker 1975; Bezzerides and Bestgen 2002). Bluehead sucker have been extirpated in the Gunnison River, Colorado above the Aspinall Unit Reservoirs (Wiltzius 1978). Bluehead sucker were documented in the Escalante River during the mid to late 1970's, but were absent from samples collected in recent years (Mueller et al. 1998). Bluehead sucker are listed as a species of concern by the states of Utah and Wyoming. In Wyoming, hybridization with white sucker appears to be compromising the genetic purity of several populations of bluehead sucker.

Recent investigation of historical accounts, museum specimens, and comparison with recent observations suggests that flannelmouth suckers occupy approximately 50% of their historic range in the upper CRB (Utah, Wyoming, Colorado, and New Mexico; Bezzerides and Bestgen 2002). Their relative abundance in the Green River tributaries is not well known. Populations have declined since the 1960's due to impoundment in the mainstem Green River in Wyoming (Flaming Gorge, Fontenelle Reservoir) and in the Colorado River in Glen Canyon, Utah (Lake Powell). Flannelmouth sucker are listed as species of concern by the states of Arizona, Utah, Colorado, and Wyoming.

XVI. RANGE-WIDE CONSERVATION OF ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER

Goal

The goal of this strategy is to outline measures that the states can implement and expand upon to ensure the persistence of roundtail chub, bluehead sucker, and flannelmouth sucker populations throughout their ranges as specified in the Conservation Agreement, and to provide guidance in the development of individual state conservation plans. The range-wide strategy will be reviewed by the signatories every five years to ensure the incorporation of new adaptive management strategies or to alter portions of the strategy to better-fit existing conditions.

Objectives

The individual state signatories to the Conservation Agreement for the three species (signatories) will develop conservation and management plans for any or all of the three species that occur naturally within their states. Any future signatories may also choose to develop individual conservation and management plans or to integrate their efforts with existing plans. The individual signatories agree to develop information and conduct actions to support the following objectives:

- Establish and/or maintain roundtail chub, flannelmouth sucker and bluehead sucker populations sufficient to ensure persistence of each species within their ranges.
 - 1) Establish measureable criteria to evaluate the number of populations necessary to maintain the three species throughout their respective ranges.
 - 2) Establish measureable criteria to evaluate the number of individuals necessary within each population to maintain the three species throughout their respective ranges.
- Establish and/or maintain sufficient connectivity between populations so that viable metapopulations are established and/or maintained.
- As feasible, identify, significantly reduce and/or eliminate threats to the persistence of roundtail chub, bluehead sucker, and flannelmouth sucker that: 1) may warrant or maintain their listing as a sensitive species by state and federal agencies, and 2) may warrant their listing as a threatened or endangered species under the ESA.

XVII. CONSERVATION ACTIONS AND ADAPTIVE MANAGEMENT

The signatories will review and document existing and ongoing programmatic actions that benefit the three species. Signatories will identify information gaps regarding species distribution, status, and life history requirements, and develop research and analysis programs to fill those gaps. Through coordination with other states, the signatories to the Conservation Agreement will develop and implement conservation and management plans for each state. The

signatories agree that the goals and objectives are appropriate across the respective ranges of the three species, though they acknowledge that as more information is gathered, the objectives may change with a consensus of the signatories to better allow for implementation of the Agreement according to the new information. Signatories also agree to incorporate the preceding conservation actions into their conservation and management plans as applicable, though each management plan should also incorporate the ability to adapt to new information and to incorporate new information where necessary. As signatories develop their individual management plans for conservation of the three species, each signatory may include but is not limited or obligated to incorporate the following conservation actions within their plans:

- 1) Conduct status assessment of roundtail chub, bluehead sucker, and flannelmouth sucker.
 - Identify concurrent programs that benefit the three fish species. Monitor and summarize activities and progress.
 - Establish current information regarding species distribution, status, and habitat conditions as the baseline from which to measure change.
 - Identify threats to population persistence.
 - Locate populations of the subject species to determine status of each.
- 2) Establish and maintain a database of past, present, and future information on roundtail chub, bluehead sucker, and flannelmouth sucker.
 - Establish format and maintain compatible databases. Signatories have identified the need to maintain a range-wide database as the primary means to conduct a range-wide assessment.
 - Establish and maintain bibliography of subject species.
- 3) Determine roundtail chub, bluehead sucker, and flannelmouth sucker population demographics, life history, habitat requirements, and conservation needs.

- Determine current population sizes of subject species and/or utilize auxiliary catch and effort data to identify trends in relative abundance.
 - Identify subject species habitat requirements and current habitat conditions through surveys and studies of hydrological, biological and watershed features.
 - Determine if existing flow recommendations and regimes are adequate for all life stages of the subject species. Develop appropriate flow recommendations for areas where existing flow regimes are inadequate.
 - Where additional data is needed to determine appropriate management actions, conduct appropriate, focused research and apply results.
- 4) Genetically and morphologically characterize populations of roundtail chub, bluehead sucker, and flannelmouth sucker.
- Determine if known information is adequate to answer management questions related to conservation genetics and assess need for additional genetic characterization of subject species.
 - Apply new information to management strategies.
 - Review the literature available on hybridization and adequacy of existing data to characterize the degrees of threats to conservation of the three species posed by hybridization.
 - Develop genetic management plans for all three species that outline maintenance of species at the population level and discuss application to reestablishment efforts.
- 5) Increase roundtail chub, bluehead sucker, and flannelmouth sucker populations to accelerate progress toward attaining population objectives for respective species.
- Assure regulatory protection for three species is adequate within the signatory states.

- 6) Enhance and maintain habitat for roundtail chub, bluehead sucker, and flannelmouth sucker.
 - Enhance and/or restore connectedness and opportunities for migration of the subject species to disjunct populations where possible.
 - Restore altered channel and habitat features to conditions suitable for the three species.
 - Provide flows needed for all life stages of the subject species.
 - Maintain and evaluate fish habitat improvements throughout the range.
 - Install regulatory mechanisms for the long-term protection of habitat (e.g., conservation easements, water rights, etc.).
- 7) Control (as feasible and where possible) threats posed by nonnative species that compete with, prey upon, or hybridize with roundtail chub, bluehead sucker, and flannelmouth sucker.
 - Determine where detrimental actions occur between the subject species and sympatric nonnative species.
 - Control detrimental nonnative fish where necessary and feasible.
 - Evaluate effectiveness of nonnative control efforts.
 - Develop multi-state nonnative stocking procedure agreements that protect all three species and potential reestablishment sites.
- 8) Expand roundtail chub, bluehead sucker, and flannelmouth sucker population distributions through transplant, augmentation (i.e., use of artificially propagated stock), or reintroduction activities as warranted using a genetically based augmentation/reestablishment plan.
- 9) Establish and implement qualitative and quantitative long-term population and habitat monitoring programs for roundtail chub, bluehead sucker, and flannelmouth sucker.

- Develop and implement monitoring plan for the subject species.
 - Evaluate conditions of populations using baseline data.
 - Develop and implement habitat monitoring plan for the subject species.
 - Evaluate habitat conditions using baseline data.
- 10) Implement an outreach program (e.g., development of partnerships, information and education activities) regarding conservation and management of roundtail chub, bluehead sucker, and flannelmouth sucker.

LITERATURE CITED

- Allen, E.J., J.M. Harris, and L.J.S. Allen. 1992. Persistence-time models for use in viability analyses of vanishing species. *Journal of Theoretical Biology* 155:33-53.
- Anderson, R.M., and G. Stewart. 2003. Riverine fish flow investigations. Biologically based instream flow recommendations for the Yampa River, the Colorado River in the 15-mile reach, and the Dolores River. Final Report to CDOW, Federal Aid project F-289-R6. Fort Collins, CO.
- Andreason, J.K. 1973. Reproductive life history of *Catostomus ardens* and *Catostomus discobolus* in the Weber River, Utah. M.S. Thesis, Department of Zoology, Brigham Young University.
- Baird, S.F., and C. Girard. 1853a. Descriptions of new species of fishes collected by Mr. John H. Clark, on the U.S. and Mexican Boundary Survey, under Lt. Col. Jas. D. Graham. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 4:387-390.
- Baxter, G.T., and M.D. Stone. 1995. Fishes of Wyoming. Wyoming Game and Fish Department, Cheyenne.
- Behnke, R.J. 1980. The impacts of habitat alterations on the endangered and threatened fishes of the Upper Colorado River Basin. Pages 204-216, *In: Energy Development in the Southwest*, Volume 2. Walter O. Spofford, Jr., Alfred L. Parker, and Allen V. Kneese, editors. Resources for the Future, Inc. Baltimore, Maryland.
- Bestgen, K.R. 2000. Personal communication with Director of Colorado State University's Larval Fish Lab, Fort Collins, Colorado.
- Bestgen, K.R., and D.L. Propst. 1989. Distribution, status, and notes on the ecology of *Gila robusta* (Cyprinidae) in the Gila River drainage, New Mexico. *The Southwestern Naturalist*, 34(3):402-412.

- Bezzerrides, N., and K.R. Bestgen. 2002. Draft Final Report: Status Review of Roundtail Chub *Gila robusta*, Flannelmouth Sucker *Catostomus latipinnis*, and Bluehead Sucker *Catostomus discobolus* in the Colorado River Basin. Submitted to U.S. Department of the Interior, Bureau of Reclamation, Salt Lake City, Utah. Larval Fish Laboratory Contribution 118, Colorado State University, Ft. Collins.
- Brouder, M.J., D.D. Rogers, and L.D. Avenetti. 2000. Life history and ecology of the roundtail chub (*Gila robusta*) from two streams in the Verde River Basin. Technical Guidance Bulletin No. 3 – July 2000. Arizona Game and Fish Department Research Branch, Federal Aid in Sportfish Restoration Project F-14-R, Phoenix.
- Brunson, R. E. 2001. Early life-stage and fish community investigations in the Duchesne River 1997 – 1999. Draft report for the Upper Colorado River Recovery Program. Utah Division of Wildlife Resources, Vernal.
- Brunson, R. and K. Christopherson. 2001. Development of a northern pike control program in the Middle Green River. Annual Report to Upper Colorado River Recovery Implementation Program. Utah Division of Wildlife Resources, Vernal.
- Buth, D.G., R.W. Murphy, and L. Ulmer. 1987. Population differentiation and introgressive hybridization of the flannelmouth sucker and of hatchery and native stocks of the razorback sucker. Transactions of the American Fisheries Society 116:103-110.
- Carlson, C.A., and R.T. Muth. 1989. Colorado River: lifeline of the American southwest. Pages 220-239 *In*: Proceedings of the international large rivers symposium. D. P. Dodge, editor. Special Publication 106. Canadian Fisheries Aquatic Sciences, Ottawa, Ontario, Canada.
- Cavalli, P.A. 1999. Fish community investigations in the Lower Price River, 1996-1997. Final Report to the Recovery Implementation Program for the Endangers Fish Species in the Upper Colorado River Basin. Project No. 78. Utah Division of Wildlife Resources, Salt Lake City, Utah.
- Chambers, S.M. 1980. Genetic divergence between populations of *Goniobasis* (Pleuroceridae) occupying different drainage systems. Malacologia 20:63-81.

- Chambers, S.M., and J.W. Bayless. 1983. Systematics, conservation and the measurement of genetic diversity. Pages 349-363 in: C.M. Schonewald-Cox et al., eds., Genetics and Conservation. Benjamin/Cummings Publishing Co., Menlo Park, CA.
- Chart, T.E. 1987. The initial effect of impoundment on the fish community of the White River, Colorado. Master's thesis, Colorado State University, Ft. Collins, Colorado.
- Chart, T.E. and E.P. Bergersen. 1992. Impact of mainstream impoundment on the distribution and movements of the resident flannelmouth sucker (Catostomidae: *Catostomus latipinnis*) population in the White River, Colorado. Southwestern Naturalist, 37:9-15.
- Chart, T.E., and L. Lenstch. 1999. Flow effects on humpback chub (*Gila cypha*) in Westwater Canyon. Project Aspinnall-46. Utah Division of Wildlife Resources, Salt Lake City, UT.
- Childs, M.R., R.W. Clarkson, and A.T. Robinson. 1998. Resource use by larval and early juvenile native fishes in the Little Colorado River, Grand Canyon, Arizona. Transactions of the American Fisheries Society 127:620-629.
- Coburn, M.M. and T.M. Cavender. 1992. Interrelationships of North American Cyprinid Fishes, *in* R.L. Mayden (ed.). Systematics, Historical Ecology, and North American Freshwater Fishes. Stanford University Press, Stanford, California.
- Connell, J.H. and W.P. Sousa. 1983. On the evidence needed to judge ecological stability or persistence. The American Naturalist 121(6):789-823.
- Cope, E.D. 1872. Recent reptiles and fishes. Report on the reptiles and fishes obtained by the naturalists of the expedition. Pages 432-443 *In*: Part IV: Special Reports, in: Preliminary report of the U.S. Geological Survey of Wyoming and portions of contiguous territories, by F. V. Hayden.
- DeMarais, B.D., T.E. Dowling, M.E. Douglas, W.L. Minckley and P.C. Marsh. 1992. Origin of *Gila seminuda* (Teleostei: Cyprinidae) through introgressive hybridization: implications for evolution and conservation. Proceedings of the National Academy of Sciences, USA 89:2747-2751.
- Douglas, M.R. and M.E. Douglas. 2003. Yampa River hybrid sucker genetic assessment. Department of Fishery and Wildlife Biology, Colorado State University, Fort Collins, CO.

- Douglas, M.E., and P.C. Marsh. 1998. Population and survival estimates of *Catostomus latipinnis* in Northern Grand Canyon, with distribution and abundance of hybrids with *Xyrauchen texanus*. *Copeia*, 1998(4):915-925.
- Dowling, T.E. and B.D. DeMarais. 1993. Evolutionary significance of introgressive hybridization in cyprinid fishes. *Nature* 362:444-446.
- Evermann, B.W., and C. Rutter. 1895. The fishes of the Colorado Basin. U.S. Fish Commission Bulletin, 14:473-486.
- Franklin, R. (ed.). 1983. Heterosis: reappraisal of theory and practice. Springer-Verlag, Berlin.
- Hallerman, E.M. 2003. Population Viability Analysis. Pages 403-417 in E.M. Hallerman, ed. Population genetics: Principles and Applications for Fisheries Scientists. American Fisheries Society, Bethesda, Maryland.
- Hamrick, J.L. 1983. The distribution of genetic variation within and among natural plant populations. Pages 335-348 in: C.M. Schonewald-Cox et al., eds., Genetics and Conservation. Benjamin/Cummings Publishing Co., Menlo Park, CA.
- Hanski, I. And M.E. Gilpin. 1991. Metapopulation dynamics: brief history and conceptual domain. *Biological Journal of the Linnaean Society* 42:3-16.
- Hawkins, J.A. and T.P. Nesler. 1991. Nonnative fishes of the Upper Colorado River Basin: an issue paper. Final Report. Larval Fish Laboratory, Colorado State University, Fort Collins, CO.
- Holden, P.B. 1973. Distribution, abundance and life history of the fishes in the upper Colorado River Basin. A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Wildlife Science (Ecology). Utah State University, Logan, Utah.
- Holden, P.B. and Clair B. Stalnaker. 1975. Distribution and abundance of mainstream fishes of the middle and upper Colorado River basins, 1967-1973. *Transactions of the American Fisheries Society* 104(2):217-231.

- Holden, P.B., and W.L. Minckley. 1980. *Catostomus discobolus* Cope, bluehead sucker. In: Atlas of North American Freshwater Fishes. D.S. Lee, C.R. Gilbert, C.H. Hocutt, R.E. Jenkins, D.E. McAllister, and J.R. Stauffer, Jr. (eds.). 1981. North Carolina State Museum of Natural History.
- Holden, P.B., S.J. Zucker, P.D. Abate, and R.A. Valdez. 1996. Assessment of the effects of fish stocking in the state of Utah: past, present and future. Bio/West, Inc., Logan, UT.
- Hubbs, C.L., and R.R. Miller. 1948. The zoological evidence, *in*: The Great Basin with Emphasis on Glacial and Postglacial Times. University of Utah Biological Series X(7), Salt Lake City.
- Hubbs, C.L., R.R. Miller, and L.C. Hubbs. 1974. Hydrographic History and Relict Fishes of the North-Central Great Basin. Memoirs of the California Academy of Sciences VII, San Francisco.
- Jackson, J.A. 2001. Evaluation of Stocked Larval Colorado Pikeminnow into the San Juan River: 2000. Utah Division of Wildlife Resources, Moab Field Station, Moab, Utah.
- Jordan, D.S., and B.W. Evermann. 1896. The fishes of North and Middle America: a descriptive catalogue of the species of fish-like vertebrates found in the waters of North America, north of the isthmus of Panama. Part 1. Bulletin of the United States National Museum. No. 47. Government Printing Office, Washington, D.C.
- Kaeding, L.R., B.D. Burdick, P.A. Schrader, and C.W. McAda. 1990. Temporal and spatial relations between the spawning of humpback chub and roundtail chub in the upper Colorado River. Transactions of the American Fisheries Society. 119:135-144.
- Lande, R. 1988. Genetics and demography in biological conservation. Science (241):1455-1460.
- Lee, D.S., C.R. Gilbert, C.H. Hocutt, R.E. Jenkins, D.E. McAllister, J.R. Stauffer, Jr. 1980, et seq. Atlas of North American Freshwater Fishes. North Carolina Biological Survey Publication #1980-12. North Carolina State Museum of Natural History, Raleigh.
- Lentsch, L.D., M.J. Perkins, and H. Maddux. 1995. Virgin Spinedace Conservation Agreement and Strategy. Publication 95-13, Utah Division of Wildlife Resources, Salt Lake City, UT.

- Lenstch, L.D., R.T. Muth, P.D. Thompson, B.G. Hoskins and T.A. Crowl. 1996. Options for selective control of nonnative fishes in the Upper Colorado River Basin. Final report publication number 96-14, Utah Division of Wildlife Resources, Salt Lake City, UT.
- Lenstch, L.D., C.A. Toline, J. Kershner, J.M. Hudson, and J. Mizzi. 2000. Range-wide conservation agreement and strategy for Bonneville cutthroat trout (*Oncorhynchus clarki utah*). Publication 00-19, Utah Division of Wildlife Resources, Salt Lake City, UT.
- Lenstch, L.D., M.J. Perkins, H. Maddux and T.C. Hogrefe. 2002. Virgin Spinedace Conservation Strategy. Publication 02-22, Utah Division of Wildlife Resources, Salt lake City, UT.
- Maddux, H.R., J.A. Mizzi, S.J. Weldon, and L.A. Fitzpatrick. 1995. Overview of the proposed critical habitat for the endangered and threatened fishes of the Virgin River Basin. Department of the Interior, U.S. Fish and Wildlife Service, Salt Lake City, Utah.
- Martinez, P.J., and N.P. Nibbelink. In review. Colorado nonnative fish stocking regulation evaluation. Colorado Division of Wildlife Resources, Grand Junction, CO.
- McAda, C.W. 1977. Aspects of the life history of three Catostomids native to the Upper Colorado River Basin. Master's thesis, Utah State University, Logan, Utah.
- McAda, C.W. and R.S. Wydoski. 1983. Maturity and fecundity of the bluehead sucker, *Catostomus discobolus* (Catostomidae), in the Upper Colorado River Basin, 1975-76. The Southwestern Naturalist, 28(1):120-123.
- McAda, C.W. 2003. Flow recommendations to benefit endangered fishes in the Colorado and Gunnison rivers. Project 54, Upper Colorado River Endangered Fish Recovery Program. U.S. Fish and Wildlife Service, Grand Junction, CO.
- McElroy, D.M. and M.E. Douglas. 1995. Patterns of morphological variation among endangered populations of *Gila robusta* and *Gila cypha* (Teleostei: Cyprinidae) in the Upper Colorado River basin. Copeia 1995(3): 636-649.
- McKinney, T., S.R. Rogers, and W.R. Persons. 1999. "Ecology of flannelmouth sucker in the Lee's Ferry tailwater, Colorado River, Arizona. Great Basin Naturalist 59:259-265.
- Meffe, G.K., 1996. Conservation genetics and the management of endangered fishes. Fisheries 11(1): 14-23.

- Miller, R.R. 1959. Origin and affinities of the Freshwater Fish Fauna of Western North America. Pages 187-222, *In: Zoogeography*. C. L. Hubbs, editor. American Association for the Advancement of Science Publication 51.
- Minckley, W.L. 1973. Fishes of Arizona. Arizona Game and Fish Department, Sims Printing Company, Inc., Phoenix, Arizona.
- Minckley, W.L. 1991. Native fishes of the Grand Canyon: an obituary? Pages 124-177, *In: Colorado River Ecology and Dam Management, Proceedings of a Symposium May 24-25, 1990, Santa Fe, New Mexico*. National Academy Press, Washington, D.C.
- Minckley, W.L., Dean A. Henderson, and Carl E. Bond. 1986. Geography of western North American freshwater fishes: description and relationships to intracontinental tectonism. Pages 519-613, *In: The Zoogeography of North American Freshwater Fishes*. Charles H. Hocutt and E. O. Wiley, editors. John Wiley and Sons, New York.
- Minckley, W.L. and B.D. DeMarais. 2000. Taxonomy of chubs (Teleostei, Cyprinidae, Genus *Gila*) in the American Southwest with comments on conservation. *Copeia* 2000(1):251-256.
- Minckley, W.L., P.C. Marsh, J.E. Deacon, T.E. Dowling, P.W. Hedrick, W.J. Matthews, and G. Mueller. 2003. A Conservation Plan for Native Fishes of the Lower Colorado River. *BioScience* 53(3): 219-234.
- Molles, M. 1980. The impacts of habitat alterations and introduced species on the native fishes of the Upper Colorado River Basin. Pages 163-181, *In: Energy Development in the Southwest, Volume 2*. Walter O. Spofford, Jr., Alfred L. Parker, and Allen V. Kneese, editors. Resources for the Future, Inc. Baltimore, Maryland.
- Mueller, G., L. Boobar, R. Wydoski, K. Comella, and Q. Bradwisch. 1998. Aquatic survey of the Lower Escalante River, Glen Canyon National Recreation Area, Utah, June 22-26, 1998. Preliminary report of the National Park Service and the Utah Division of Wildlife Resources.
- Mueller, G.L., and R. Wydoski. 2004. Reintroduction of the Flannelmouth Sucker in the Lower Colorado River. *North American Journal of Fisheries Management* 24(1): 41-46.

- Muth, R.T., and seven others. 2000. Flow and temperature recommendations for endangered fishes in the Green River downstream of Flaming Gorge Dam. Final report, Upper Colorado River Endangered Fish Recovery Program. Lakewood, CO.
- Ono, R.D., J.D. Williams, and A. Wagner. 1983. Vanishing fishes of North America. Stone Wall Press, Inc. Washington, D.C.
- Osmundson, D.B. 1999. Longitudinal variation in fish community structure and water temperature in the Upper Colorado River: implications for Colorado pikeminnow habitat suitability. Final Report for Recovery Implementation Program, Project No. 48. U.S. Fish and Wildlife Service, Grand Junction, Colorado.
- Peacock, M.M., and V. Kirchhoff. 2004. Assessing the conservation value of hybridized cutthroat trout populations in the Quinn River drainage, Nevada. Transactions of the American Fisheries Society 133:309-325.
- Reed, D.H. and R. Frankham. 2003. Correlation between fitness and genetic diversity. Conservation Biology 17(1) :230-237.
- Rieman, B.E., and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. USDA Forest Service, Intermountain Research Station, Ogden, Utah. General Technical Report INT-302.
- Robinson, A.T., R.W. Clarkson, and R.E. Forrest. 1998. Dispersal of larval fishes in a regulated river tributary. Transactions of the American Fisheries Society 127 :772-786.
- Roff, D.A. 1974. The analysis of a population model demonstrating the importance of dispersal in a heterogeneous environment. Oecologia 15 :259-275.
- Ryden, D.W. 2001. Long term results of sub-adult and adult large-bodied fishes in the San Juan River in 2000. U.S. Fish and Wildlife Services, Colorado River Fishery Project, Grand Junction, Colorado.
- San Juan Recovery Implementation Program. 1995. Program Document, Cooperative Agreement, Long Range Plans, and Side-by-Side Analysis: San Juan/Upper Colorado Programs. U.S. Fish and Wildlife Service, Albuquerque, NM.

- Scoppettone, G.G. 1988. Growth and longevity of the Cui-ui and longevity of other Catostomids and Cyprinids in western North America. *Transactions of the American Fisheries Society*, 117:301-307.
- Shaffer, M.L. 1987. Minimum viable populations: coping with uncertainty. Pages 69-86 in: Soulé, M.E., (ed.). *Viable populations for conservation*. Cambridge University Press, Cambridge, Massachusetts.
- Siebert, D.J. 1980. Movements of fishes in Aravaipa Creek, Arizona. M.S. Thesis, Arizona State University, Tempe.
- Sigler, W.F. and R.R. Miller. 1963. *Fishes of Utah*. Utah State Department of Fish and Game, Salt Lake City, Utah.
- Sigler, W.F. and J.W. Sigler. 1996. *Fishes of Utah: A Natural History*. University of Utah Press, Salt Lake City.
- Simberloff, D. and L.G. Abele. 1976. Refuge design and island biogeographic theory: effects of fragmentation. *The American Naturalist* 120(1):41-50.
- Stearns, S.C. 1993. *The evolution of life histories*. Oxford University Press, New York. 249p.
- Soulé, M.E. (ed.). 1980. Threshold for survival: maintaining fitness and evolutionary potential. Pages 151-170 in: Soulé, M.E. and B.A. Wilcox, eds., *Conservation biology: an evolutionary-ecological approach*. Sinauer Associates, Massachusetts.
- Soulé, M.E. (ed.). 1986. *Conservation Biology: the Science of Scarcity and Diversity*. Sinauer Associates, Massachusetts.
- SWCA, Inc., Environmental Consultants. 2002. Nonnative fish control feasibility study to benefit June sucker in Utah Lake. SWCA, Inc., Environmental Consultants, Salt Lake City, UT.
- Suttkus, R.D. and G.H. Clemmer. 1977. The humpback chub, *Gila cypha*, in the Grand Canyon area of the Colorado River. *Occasional Papers of the Tulane University Museum of Natural History* 1:1-30

- Trammell, M.E., and seven others. 1999. Flaming Gorge studies: Assessment of Colorado pikeminnow nursery habitat in the Green River. Project 33, Upper Colorado River Endangered Fish Recovery Program. Utah Division of Wildlife Resources, Salt Lake City, UT.
- Taylor, J.N., W.R. Courtenay, Jr., and J.A. McMann. 1984. Known impacts of exotic fish introductions in the continental United States. Pages 322-373 in W.R. Courtenay, Jr. and J.R. Stauffer, Jr., editors. Distribution, biology, and management of exotic fishes. The John Hopkins University Press. Baltimore, MD.
- Tyus, H.M. and J.F. Saunders. 1996. Nonnative fishes in the Upper Colorado River Basin and a strategic plan for their control. Final report to the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin. Cooperative agreement 14-18-0006-95-923. U.S. Fish and Wildlife Service, Denver, CO.
- Tyus, H.M. and J.F. Saunders. 2001. An evaluation of the role of tributary streams for endangered fishes in the upper Colorado River basin, with recommendations for future recovery actions. Center for Limnology, University of Colorado, Boulder, CO.
- Upper Colorado River Endangered Fish Recovery Program 2002. Nonnative fish control workshop: summary, conclusions and recommendations. Program Director's Office, UCREFRP, Lakewood, CO.
- U.S. Fish and Wildlife Service. 1995. Virgin River Fishes Recovery Plan. U.S. Fish and Wildlife Service, Denver, CO.
- U.S. Fish and Wildlife Service. 1999. June sucker (*Chasmistes liorus*) recovery plan. U.S. Fish and Wildlife Service, Denver, CO.
- U.S. Fish and Wildlife Service. 2003a. Endangered and threatened wildlife and plants: reconsidered finding for an amended petition to list the westslope cutthroat trout as threatened throughout its range. Federal Register 68(152):46989-47009.
- U.S. Fish and Wildlife Service. 2003b. Section 7 consultation, sufficient progress and historic projects agreement and Recovery Implementation Program Recovery Action Plan (RIPRAP). U.S. Fish and Wildlife Service, Denver, CO.

- Valdez, R.A. and G.C. Clemmer. 1982. Life history and prospects for recovery of the humpback chub and bonytail chub, *in* W.H. Miller, H.M. Tyus, and C.A. Carlson (eds.) *Fishes of the Upper Colorado River System: Present and Future*. Western Division, American Fisheries Society, Bethesda, Maryland.
- Valdez, R.A. 1990. The endangered fish of Cataract Canyon. Final Report of Bio-West, Inc., to U.S. Bureau of Reclamation, Salt Lake City, Utah.
- Valdez, R.A., and Steven W. Carothers. 1998. The aquatic ecosystem of the Colorado River in Grand Canyon: Grand Canyon Data Integration Project Synthesis Report. Dorothy A. House, editor. Prepared for the U.S.D.I. Bureau of Reclamation, Salt Lake City, Utah, by SWCA, Inc., Environmental Consultants, Flagstaff, Arizona.
- Vrijenhoek, R.C., M.E. Douglas, and G.K. Meffe. 1985. Conservation genetics of endangered fish populations in Arizona. *Science* 228:400-402.
- Voeltz, J.B. 2002. Roundtail chub (*Gila robusta*) status survey of the lower Colorado River Basin. Technical Report 186, Arizona Game and Fish Department, Phoenix.
- Wilcox, B.A. and D.D. Murphy. 1985. Conservation strategy: effects of fragmentation on extinction. *American Naturalist* 125:879-887.
- Williams, S., and W.T. Hogarth. 2003. Policy for Evaluation of Conservation Efforts When Making Listing Decisions. *Federal Register* 68(609): 15100 – 15115.
- Wiltzius, W.J. Fish Culture and Stocking in Colorado, 1872-1978. Colorado Division of Wildlife, 1985.

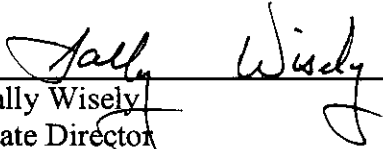
APPENDIX 1: STANDARD LANGUAGE REQUIRED BY THE STATE OF ARIZONA

The Arizona Game and Fish Commission, acting through its administrative agency, the Arizona Game and Fish Department, enters into this Agreement under authority of A.R.S. § 17-231.B.7).

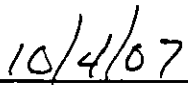
The following stipulations are hereby made part of this Agreement, and where applicable must be adhered to by all signatories to this Agreement.

- **ARBITRATION:** To the extent required pursuant to A.R.S. § 12-1518, and any successor statutes, the parties agree to use arbitration, after exhausting all applicable administrative remedies, to resolve any dispute arising out of this agreement, where not in conflict with Federal Law.
- **CANCELLATION:** All parties are hereby put on notice that this agreement is subject to cancellation pursuant to A.R.S. § 38-511.
- **OPEN RECORDS:** Pursuant to A.R.S. § 35-214 and § 35-215, and Section 41.279.04 as amended, all books, accounts, reports, files and other records relating to the contract shall be subject at all reasonable times to inspection and audit by the State for five years after contract completion. Such records shall be reproduced as designated by the State of Arizona.

The following signatories support the goals, objectives, and actions of the Conservation Agreement for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker, version 10.4.4 and agree to support the conservation efforts described.



Sally Wisely
State Director
Bureau of Land Management
Colorado State Office



Date

APPENDIX – B

Level 1 Potential Conservation Area (PCA) Report

Name San Miguel River at Tabeguache Creek

Site Code S.USCOFO*155

IDENTIFIERS

Site ID 266 **Site Class** PCA
Site Alias Campbell Creek
Site Alias Fisherman Placer
Site Alias Lower San Miguel River Preserve Site
Site Alias Spear Placer

Network of Conservation Areas (NCA)

<u>NCA Site ID</u>	<u>NCA Site Code</u>	<u>NCA Site Name</u>
1598	S.USWRO1*418	San Miguel River

Site Relations The site is almost contained in the San Miguel River (S.USWRO1*418).

LOCATORS

Nation	United States	Latitude	381944N
State	Colorado	Longitude	1084149W

Quad Code Quad Name

38108-B5	Naturita
38108-B6	Naturita NW
38108-C5	Nucla
38108-C6	Uravan
38108-D6	Atkinson Creek

County

Montrose (CO)

Watershed Code Watershed Name

14030003	San Miguel

Site Directions

From Naturita, drive north on State Highway 141 approximately 12 miles to the southern boundary of the preserve. From the mill site of Uravan, drive south on State Highway 141 about 2 miles to the point where the San Miguel River passes under the highway. The northern boundary of the preserve is about 100 yards south of the bridge. The preserve runs about 3 miles along the San Miguel River.

SITE DESCRIPTION

Minimum Elevation	5,000.00	Feet	1,524.00	Meters
Maximum Elevation	6,900.00	Feet	2,103.00	Meters

Site Description

The San Miguel River at Tabeguache site includes the riparian corridor of the San Miguel River and a small amount of the adjacent uplands. It also takes in the riparian zones of the lower part of Tabeguache Creek and Coal Canyon. Mature cottonwoods, both the narrowleaf and Rio Grande species, as well as their hybrids dominate the riparian zone. The understory consists of skunkbrush and coyote willow. The uplands have dry, rocky pinon and juniper woodland with much exposed sandstone. Most of the site is owned by The Nature Conservancy, having been donated to the organization in 1987 by the State of Colorado, after it was donated to the state by Umetco Minerals Corporation. The Conservancy recently acquired additional private land upstream of the original preserve. A total of 39 element occurrences have been recorded for the site, in part reflecting the efforts of The Nature Conservancy to thoroughly document the current vegetation. The site contains numerous high quality examples of riparian plant communities, including the globally imperiled Fremont cottonwood/skunkbrush association, the New Mexico privet riparian shrublands, and the more common Rio Grande cottonwood/coyote willow association. The San Miguel riparian zone varies from narrow and straight in incised canyons, to wide meanders that lead to a multi-layered successional pattern of plant associations on the riverbends. Shrubs generally line the channel, with upland vegetation, including sagebrush, rabbitbrush, rose and serviceberry occurring on the flat meander bends. In some areas, tamarisk has invaded the riparian vegetation, replacing the native New Mexico privet and skunkbrush. Cottonwoods and willows are reproducing successfully along the river, thanks to the natural flooding processes that can occur on this undammed river.

Key Environmental Factors

No Data

Level 1 Potential Conservation Area (PCA) Report

Name San Miguel River at Tabeguache Creek

Site Code S.USCOFO*155

Climate Description

No Data

Land Use History

No Data

Cultural Features

No Data

SITE DESIGN

Site Map Y - Yes

Mapped Date 03/01/2000

Designer Lyon, M.J. and J.R. Sovell

Boundary Justification

The site includes the riparian zones of the San Miguel River, Coal Canyon and Tabeguache Creek in the area owned by The Nature Conservancy and encompassing the element occurrences listed above. It also includes some adjacent uplands with pinon - juniper communities that are important in maintaining the quality of the riparian zone by limiting erosion and sedimentation.

Primary Area 18,972.55 Acres 7,677.95 Hectares

SITE SIGNIFICANCE

Biodiversity Significance Rank B2: Very High Biodiversity Significance

Biodiversity Significance Comments

This site contains an excellent (A-ranked) occurrence of a plant community which is imperiled globally (G2). In addition to the critically imperiled New Mexico privet riparian shrubland community, there are over 20 other targeted riparian communities within the site, including riparian forests dominated by both narrowleaf and Fremont cottonwoods (and their hybrids), and montane riparian shrublands dominated by river birch, skunkbrush, coyote willow or silver buffaloberry. There are several occurrences of rare plants; Payson lupine and San Rafael milkvetch. The rare plant populations have not been updated in recent years. Uplands include targeted plant communities, including occurrences of mesic western slope pinon - juniper woodlands, salt meadows, and western slope grasslands.

Other Values Rank No Data

Other Values Comments

This site is quite scenic and accessible to the public.

Protection Urgency Rank P4: No Threat or Special Opportunity

Protection Urgency Comments

No threat is known for the foreseeable future. Most of the site is owned by TNC. Development of the two remaining tracts, most likely for residential use, does not appear imminent, but the owner of the Curtis tract wants to sell at a reasonable price, and we should seize the opportunity to protect this parcel. Residential or other uses of the Curtis tract, which is upstream of the Conservancy's existing preserve, would adversely affect the preserve.

Management Urgency Rank M3: Needed within 5 Years to Maintain Quality

Management Urgency Comments

Ongoing, recurrent management action would help to maintain the current quality of element occurrences.

LAND MANAGEMENT ISSUES

Land Use Comments

Surrounding lands are mostly managed by Bureau of Land Management under multiple use. There is little livestock grazing of the uplands due to lack of water, scarcity of forage and steep slopes. The Superfund site at Uruan is 2 miles downstream of the site and does not adversely impact the Lower San Miguel River Preserve site.

Natural Hazard Comments

During spring runoff, the river has a swift current and is not safe for water activities such as swimming or fishing. Rattlesnakes are present.

Exotics Comments

Exotics are present, as they are on virtually all riparian sites at lower elevation in the western United States. The only woody exotic plant of any consequence is tamarisk (*Tamarix chinensis*) which is not especially

Level 1 Potential Conservation Area (PCA) Report

Name San Miguel River at Tabeguache Creek

Site Code S.USCOFO*155

abundant. Efforts to control this species were initiated in October 1990. Common exotic herbaceous plants include cheatgrass (*Bromus tectorum*), yellow sweetclover (*Melilotus officinalis*), and Kentucky bluegrass (*Poa pratensis*). However, the herbaceous understory also contains an abundance of native, perennial species, principally western wheatgrass (*Agropyron smithii*).

Offsite

Livestock grazing on adjacent public (BLM) or private lands does not appear to spill on to the preserve.

Information Needs

The rank of the Utah juniper / Utah serviceberry - mockorange / salina wildrye (*Juniperus osteosperma* / *Amelanchier* - *Philadelphus microphyllus* / *Elymus salina*) plant community, which is found on the uplands of the site, is unknown. This community also occurs on nearby BLM lands. There are a number of ramshackle structures on the northern (downstream) end of the site. They were supposedly built for the enjoyment of employees of the Uravan mill by Umetco. We need to determine if any of the structures have any historic value.

Management Needs

An element stewardship abstract for the Rio Grande cottonwood / skunkbrush (*Populus deltoides* ssp. *wislizenii* / *Rhus trilobata*) plant community was prepared in 1990. Element Stewardship Abstracts for the globally-endangered Rio Grande cottonwood / Coyote willow (*Populus deltoides* ssp. *wislizenii* / *Salix exigua*) plant community and the Utah juniper / Salina wildrye (*Juniperus osteosperma* / *Elymus salina*) plant community need to be prepared. A management plan for the site was also completed in 1990. There are a number of ramshackle structures on the northern (downstream) end of the site. The structures need to be removed if they are not of any historical value. Umetco has indicated a willingness to provide a truck, front end loader and operators for this work.

Managed Area Relations

BLM has suggested that the Tabeguache Creek WSA be managed as an Outstanding Natural Area, and that recreation use may be incompatible with this proposed management direction (USDI 1985). If designated an ONA by Congress, visitor use of the area could be limited to educational and scientific purposes. An ORV closure, and no surface occupancy stipulations for oil and gas leasing would protect the integrity of the main canyon. Management on the Nature Conservancy property has included annual removal of tamarisk by volunteers. This has proved successful, although labor intensive. Further survey effort is needed to update the populations of Payson lupine and San Rafael milkvetch. The Payson lupine populations recorded here are important in connecting the two other major locations known for the species, represented in the Highway 141 and 145 site and the three sites in the Paradox Valley.

Protection Comments

Approximately 77% of this site is owned by BLM, while the remaining 23% is privately owned. The majority of the private land is included within The Nature Conservancy's Lower San Miguel Preserve. This is one of three Nature Conservancy Preserves on the San Miguel River, representing the lowest elevations, while the other two are in middle and high elevation sections. BLM lands at Tabeguache Creek are included in a Wilderness Study Area, but were found not to be suitable for wilderness designation by BLM in 1985 (USDI 1985). The Resource Management Plan points out that the area is sensitive both ecologically and archaeologically, but these values can be better protected by designating the site as an Outstanding Natural Area (ONA). [Neely 91-01-04] The largest tract (204 acres) was donated to the Conservancy in 1988. The second tract (Curtis) is under option for a purchase price of \$5000. Preliminary discussions with the owner of the third tract indicate owner is willing to sell.

ASSOCIATED ELEMENTS OF BIODIVERSITY

<u>Element</u> <u>State ID</u>	<u>State Scientific Name</u>	<u>State Common Name</u>	<u>Global</u> <u>Rank</u>	<u>State</u> <u>Rank</u>	<u>Driving</u> <u>Site Rank</u>
18466	<i>Lupinus crassus</i>	Payson lupine	G2	S2	No
18466	<i>Lupinus crassus</i>	Payson lupine	G2	S2	No
18466	<i>Lupinus crassus</i>	Payson lupine	G2	S2	No
18466	<i>Lupinus crassus</i>	Payson lupine	G2	S2	No
20453	<i>Astragalus linifolius</i>	Grand Junction milkvetch	G3Q	S3	No
22406	<i>Astragalus rafaensis</i>	San Rafael milkvetch	G2G3	S1	No
16839	<i>Rhus trilobata</i> Shrubland	Skunkbrush Riparian Shrubland	G2	S2	Yes
16839	<i>Rhus trilobata</i> Shrubland	Skunkbrush Riparian Shrubland	G2	S2	No

Level 1 Potential Conservation Area (PCA) Report

Name	San Miguel River at Tabeguache Creek	Site Code	S.USCOFO*155	
16839	<i>Rhus trilobata</i> Shrubland	Skunkbrush Riparian Shrubland	G2	S2 No
18131	<i>Pleuraphis jamesii</i> Herbaceous Vegetation	Western Slope Grasslands	G2G4	S1 No
24600	<i>Populus deltoides</i> ssp. <i>wislizeni</i> / <i>Rhus trilobata</i> Woodland	Fremont's Cottonwood Riparian Forests	G2	S2 Yes
24600	<i>Populus deltoides</i> ssp. <i>wislizeni</i> / <i>Rhus trilobata</i> Woodland	Fremont's Cottonwood Riparian Forests	G2	S2 No
24600	<i>Populus deltoides</i> ssp. <i>wislizeni</i> / <i>Rhus trilobata</i> Woodland	Fremont's Cottonwood Riparian Forests	G2	S2 Yes
24634	<i>Populus deltoides</i> ssp. <i>wislizeni</i> / <i>Salix exigua</i> Woodland	Fremont's Cottonwood Riparian Forests	G3	S1S2 No
24634	<i>Populus deltoides</i> ssp. <i>wislizeni</i> / <i>Salix exigua</i> Woodland	Fremont's Cottonwood Riparian Forests	G3	S1S2 No
24634	<i>Populus deltoides</i> ssp. <i>wislizeni</i> / <i>Salix exigua</i> Woodland	Fremont's Cottonwood Riparian Forests	G3	S1S2 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Narrowleaf	G3	S3 No
24619	<i>Populus angustifolia</i> / <i>Rhus trilobata</i> Woodland	Cottonwood/Skunkbrush	G3	S3 No
24830	<i>Pinus edulis</i> - <i>Juniperus</i> spp. / <i>Cercocarpus montanus</i> Woodland	Mesic Western Slope Pinyon-Juniper Woodlands	G5	S4 No
24637	<i>Betula occidentalis</i> / Mesic Graminoids Shrubland	Lower Montane Riparian Shrublands	G3	S2 No
24637	<i>Betula occidentalis</i> / Mesic Graminoids Shrubland	Lower Montane Riparian Shrublands	G3	S2 No
19429	<i>Sporobolus airoides</i> Southern Plains Herbaceous Vegetation	Great Plains Salt Meadows	G3Q	S3 No
19709	<i>Forestiera pubescens</i> Shrubland	Foothills Riparian Shrubland	G1G2	S1 Yes
19709	<i>Forestiera pubescens</i> Shrubland	Foothills Riparian Shrubland	G1G2	S1 Yes
19709	<i>Forestiera pubescens</i> Shrubland	Foothills Riparian Shrubland	G1G2	S1 Yes
19709	<i>Forestiera pubescens</i> Shrubland	Foothills Riparian Shrubland	G1G2	S1 Yes
24984	<i>Juniperus osteosperma</i> Woodland	Mesic Western Slope Pinyon-Juniper Woodlands	G5	SU No
24984	<i>Juniperus osteosperma</i> Woodland	Mesic Western Slope Pinyon-Juniper Woodlands	G5	SU No
24984	<i>Juniperus osteosperma</i> Woodland	Mesic Western Slope Pinyon-Juniper Woodlands	G5	SU No
17439	<i>Shepherdia argentea</i> Shrubland	Foothills Riparian Shrubland	G3G4	S1 No
17439	<i>Shepherdia argentea</i> Shrubland	Foothills Riparian Shrubland	G3G4	S1 No
24659	<i>Salix exigua</i> / Barren Shrubland	Coyote Willow/Bare Ground	G5	S5 No
24659	<i>Salix exigua</i> / Barren Shrubland	Coyote Willow/Bare Ground	G5	S5 No
40542	<i>Juniperus osteosperma</i> / <i>Leymus salinus</i> spp. <i>salinus</i> Wooded Herbaceous Vegetation	Mesic Western Slope Pinyon-Juniper Woodlands	G3	S3 No
40542	<i>Juniperus osteosperma</i> / <i>Leymus salinus</i> spp. <i>salinus</i> Wooded Herbaceous Vegetation	Mesic Western Slope Pinyon-Juniper Woodlands	G3	S3 No
40542	<i>Juniperus osteosperma</i> / <i>Leymus salinus</i> spp. <i>salinus</i> Wooded Herbaceous Vegetation	Mesic Western Slope Pinyon-Juniper Woodlands	G3	S3 No

Level 1 Potential Conservation Area (PCA) Report

Name San Miguel River at Tabeguache Creek

Site Code S.USCOFO*155

REFERENCES

Reference ID

192792

Full Citation

Lyon, P. and J. Sovell. 2000. Final Report: A Natural Heritage Assessment, San Miguel and Western Montrose Counties, Colorado. Colorado Natural Heritage Program, Fort Collins, CO.

ADDITIONAL TOPICS

Additional Topics

No Data

VERSION

Version Date 03/01/2000

Version Author Lyon, M.J. and J.R. Sovell

Level 1 Potential Conservation Area (PCA) Report

Name Uravan West

Site Code S.USWRO1*58

IDENTIFIERS

Site ID 1914 Site Class PCA

Site Alias None

Network of Conservation Areas (NCA)

<u>NCA Site ID</u>	<u>NCA Site Code</u>	<u>NCA Site Name</u>
1598	S.USWRO1*418	San Miguel River

Site Relations Shares a small portion of its western boundary with Dolores Canyon South (S.USCOHP*4644) and overlaps San Miguel River NCA (S.USWRO1*418).

LOCATORS

Nation	United States	Latitude	382238N
State	Colorado	Longitude	1084608W

Quad Code Quad Name

38108-C6	Uravan
38108-C7	Davis Mesa
38108-D6	Atkinson Creek
38108-D7	Red Canyon

County

Montrose (CO)

Watershed Code Watershed Name

14030002	Upper Dolores
14030003	San Miguel
14030004	Lower Dolores

Site Directions

The Uravan West site extends along the San Miguel River for 4.5 miles north of Uravan, Colorado in Montrose County.

SITE DESCRIPTION

Minimum Elevation	5,100.00	Feet	1,554.00	Meters
Maximum Elevation	5,800.00	Feet	1,768.00	Meters

Site Description

This site includes alluvial terraces of the San Miguel River, and the adjacent slickrock of the Entrada Formation, as well as some pinon - juniper uplands in the Morrison Formation. The narrowly confined riparian zone has a band of New Mexico privet. Other riparian species include river birch and coyote willow. In disturbed areas, upland vegetation such as rabbitbrush mixes with the riparian species. Hillsides and adjacent mesas are vegetated with sparse pinyon, juniper, and sagebrush. San Rafael milkvetch was found to be quite abundant south of the San Miguel River. Associated species at that location included antelope bitterbrush, mountain mahogany, single leaf ash, sand aster, many-lobed groundsel, large-flowered breadroot, and chainpod. It includes the Umetco uranium mine, and has been subject to disturbances associated with mining for over 50 years.

Key Environmental Factors

No Data

Climate Description

No Data

Land Use History

No Data

Cultural Features

No Data

SITE DESIGN

Site Map	Y - Yes	Mapped Date	03/13/2000
Designer	Lyon, M.J. and J.R. Sovell		

Level 1 Potential Conservation Area (PCA) Report

Name Uravan West

Site Code S.USWRO1*58

Boundary Justification

The boundary encloses the riparian zone of the San Miguel River between Uravan and the confluence with the Dolores River. It also includes adjacent uplands that are the habitat of the San Rafael/Grand Junction milkvetch. The exact location of the brimstone clubtail, a dragonfly, is unknown. It may have been collected from one of the San Miguel's tributaries in this area.

Primary Area 4,026.60 Acres 1,629.51 Hectares

SITE SIGNIFICANCE

Biodiversity Significance Rank B2: Very High Biodiversity Significance

Biodiversity Significance Comments

This site contains a good (B-ranked) occurrence of a plant community which is critically imperiled on a global scale (G1G2/S1), *Forestiera pubescens*, a good (B-ranked) occurrence of a globally vulnerable (G3/S2) community, *Betula occidentalis* / mesic graminoid, and an unranked of the globally imperiled (G2G3/S1) San Rafael milkvetch (*Astragalus rafaensis*).

Other Values Rank No Data

Other Values Comments

No Data

Protection Urgency Rank P4: No Threat or Special Opportunity

Protection Urgency Comments

No threat is known for the foreseeable future.

Management Urgency Rank M4: Not Needed Now; No Current Threats; May Need in Future

Management Urgency Comments

Although not urgently required, management may be needed in the future to maintain the current quality of element occurrences.

LAND MANAGEMENT ISSUES

Land Use Comments

No Data

Natural Hazard Comments

No Data

Exotics Comments

No Data

Offsite

No Data

Information Needs

No Data

Management Needs

No Data

Managed Area Relations

This section of the San Miguel River has been heavily impacted by mining for many years. Restoration of mined lands is underway. However, restoration of the site to a completely natural condition is probably not feasible.

Protection Comments

The site contains about equal amounts of BLM and private mining land in a complex pattern. Although no uranium mining is taking place currently, the potential remains as a future threat.

ASSOCIATED ELEMENTS OF BIODIVERSITY

<u>Element</u>			<u>Global</u>	<u>State</u>	<u>Driving</u>
<u>State ID</u>	<u>State Scientific Name</u>	<u>State Common Name</u>	<u>Rank</u>	<u>Rank</u>	<u>Site Rank</u>
24637	<i>Betula occidentalis</i> / Mesic Graminoids	Lower Montane Riparian	G3	S2	No
	Shrubland	Shrublands			
19709	<i>Forestiera pubescens</i> Shrubland	Foothills Riparian Shrubland	G1G2	S1	Yes
22406	<i>Astragalus rafaensis</i>	San Rafael milkvetch	G2G3	S1	No

Level 1 Potential Conservation Area (PCA) Report

Name Uravan West

Site Code S.USWRO1*58

REFERENCES

<u>Reference ID</u>	<u>Full Citation</u>

-	No Data

ADDITIONAL TOPICS

Additional Topics

No Data

VERSION

Version Date 03/13/2000

Version Author Lyon, M.J. and J.R. Sovell

APPENDIX – C

Fish Sampling Report

Dan Kowalski
Aquatic Biologist
Southwest Region



Water: San Miguel River Uravan to Dolores Confluence
Date: 7/15/2008
Gear: 14 ft. electrofishing raft with Smith Root 2.5GPP
Drainage: Dolores
Water Codes: 46842

OBJECTIVE

The San Miguel River from Uravan to the Dolores confluence was sampled with one pass CPUE electrofishing to monitor native fish populations. The station began at the Uravan USGS gage and ended at the confluence with the Dolores and was 6.9 miles long.

RESULTS

The results of the survey are summarized in Table 1 and length frequency histograms of the native fish are presented in Figures 1-3. Seventy-two percent of the fish sampled were native species. This reach of the San Miguel contains excellent populations of flannemouth suckers and bluehead suckers represented by multiple age classes including many large adults. This reach appears to be one the best populations of these two native suckers in the Dolores River basin and contains much larger individuals than most sites on the main stem Dolores.

Species	# Caught	% Catch	Mean Length (in.)	Length Range (in.)
Flannemouth Suckers	155	35	14.5	5.7-21.3
Bluehead Suckers	140	32	10.2	5.0-15.7
Roundtail Chubs	19	4	8.2	6.0-16.2
Channel Catfish	117	27	12.6	7.9-19.4
Speckled Dace	6	1	3.4	2.7-4.3

Table 1. Summary of fish sampled in 2008 on the San Miguel River below Uravan.

CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

The lower San Miguel River contains an excellent native fish community and should continue to be managed as a category 100 native fish conservation water. Efforts should be taken to protect the flow regime of this reach of river including spring peak flows and especially base flows. Major tributaries like Tabeguache Creek and Atkinson Creek that could be used seasonally for spawning should also be protected. The San Miguel River has a relatively natural hydrograph as far as spring peak flows but is impacted by water diversions in the late summer severely reducing base flows (Figures 4 and 5). Of special concern is the late summer period from about mid August to October when base flows in the upper basin average around 100 cfs at Placerville but routinely drop to near 50 cfs at Uravan. The decreased instream flows in late summer not only degrade the quality and quantity of native fish habitat but provide conditions more favorable to non-native fish like channel catfish and smallmouth bass. The Dolores River upstream from the confluence has been impacted by low base flows and the San Miguel could be acting as a refuge for suckers in the lower river. Management efforts should also be taken to prevent the further introduction of nonnative fish and to minimize the numbers and spread of channel catfish and smallmouth bass in the river.

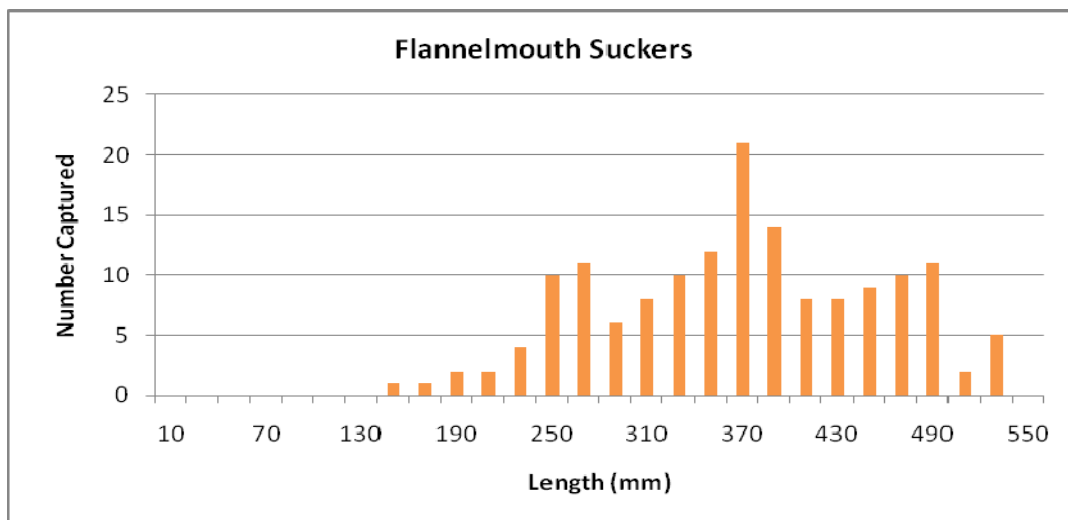


Figure 1. Length frequency histogram of flannelmouth suckers captured in the San Miguel below Uravan in 2008.

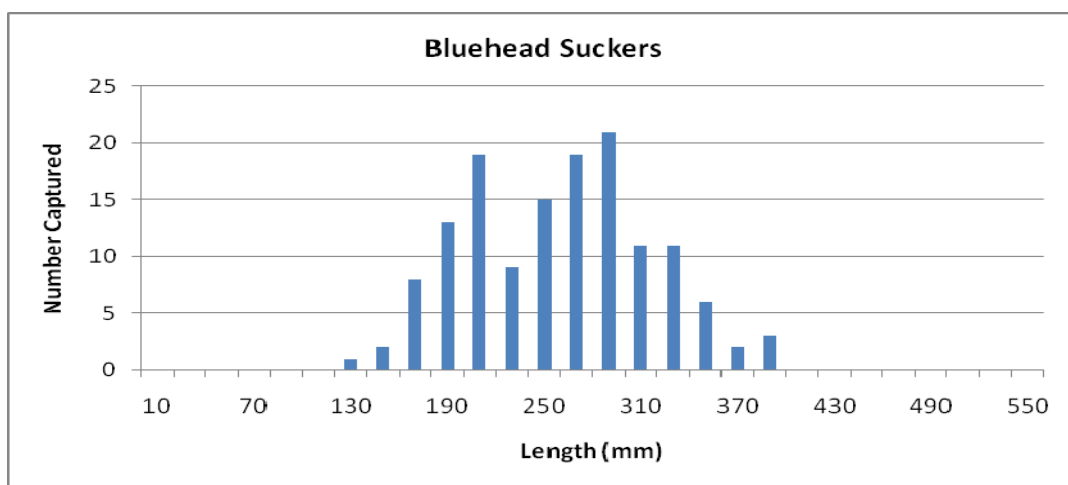


Figure 2. Length frequency histogram of bluehead suckers captured in the San Miguel below Uravan in 2008.

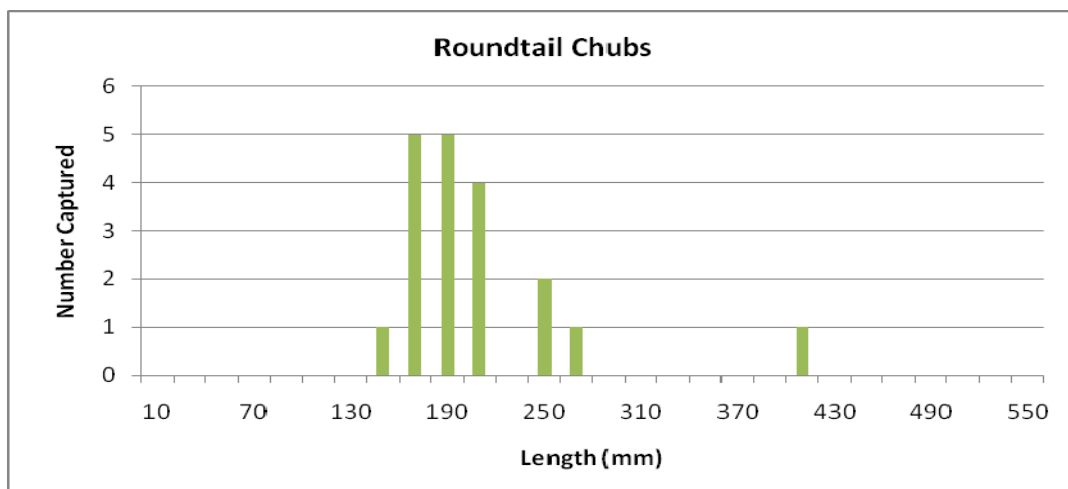


Figure 3. Length frequency histogram of roundtail chubs captured in the San Miguel below Uravan in 2008.

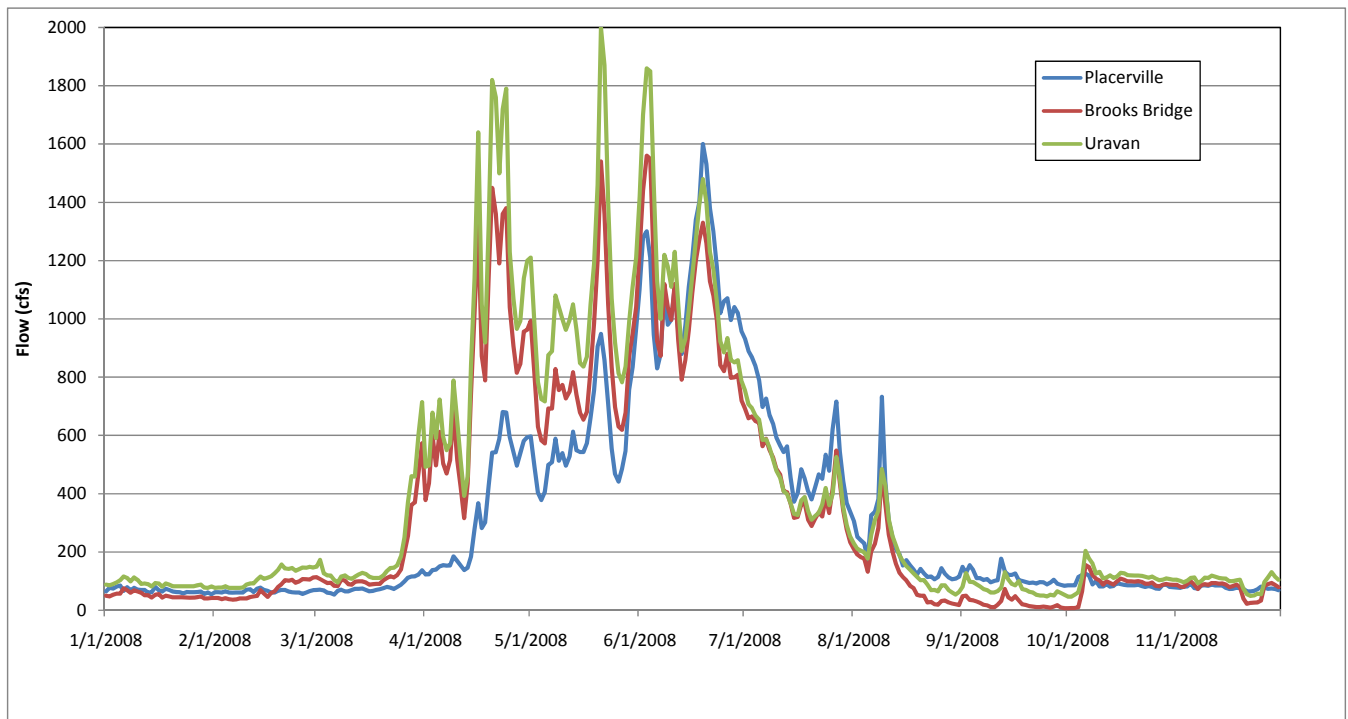


Figure 4. San Miguel River hydrograph 2008.

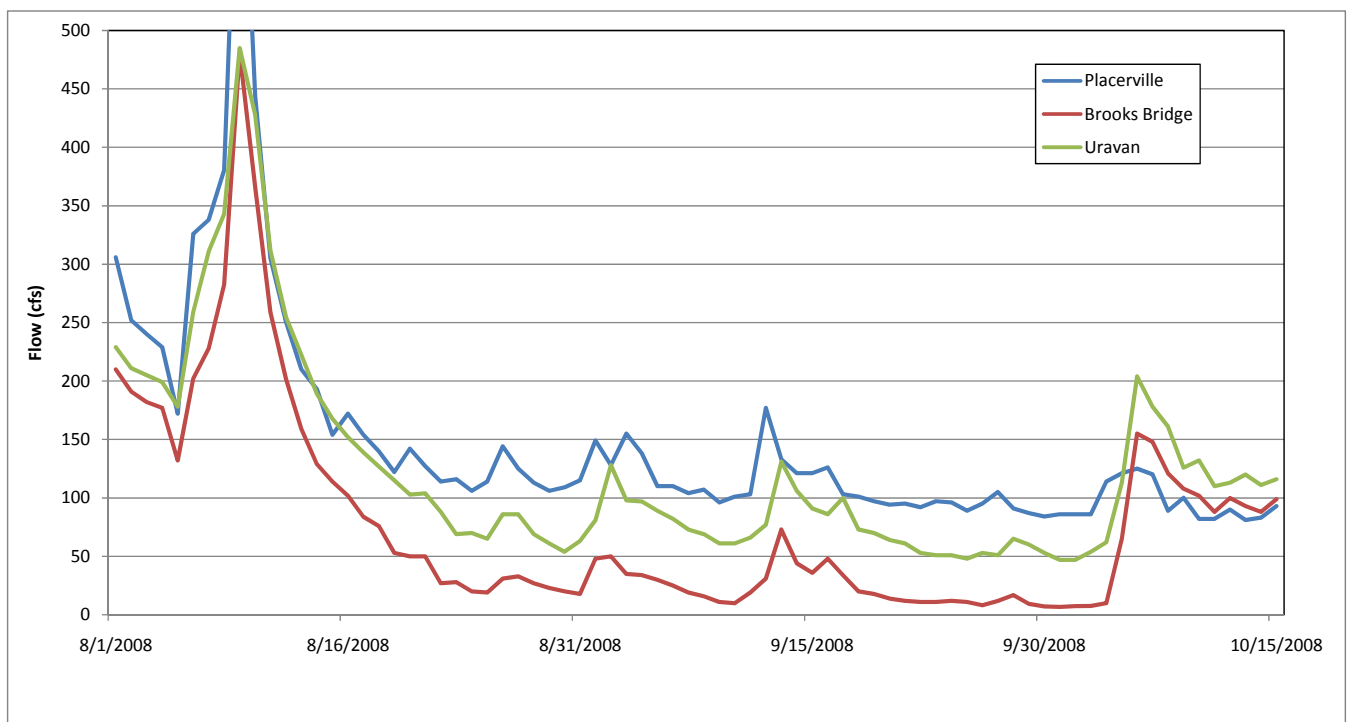


Figure 5. San Miguel River hydrograph for the late summer to fall period 2008.

APPENDIX – D

Aquatic Macroinvertebrate Monitoring Report

Report Prepared for:
U.S. Bureau of Land Management
Montrose Field Office
2465 South Townsend Avenue
Montrose, Colorado 81401

2000

SM only

Report Prepared by:
Mark Vinson
National Aquatic Monitoring Center
Department of Fisheries & Wildlife
Utah State University
Logan, Utah 84322-5210
3 November 2000



Sampling Locations

The information in this report is based on data collected at the sites listed below.

<u>Station</u>	<u>Waterbody</u>
SANMIGUEL1	San Miguel River above Placerville, San Miguel County, Colorado
SANMIGUEL2	San Miguel River below Beaver Creek, San Miguel County, Colorado
SANMIGUEL3	San Miguel River abv. Pinon, belw CC ditch, Montrose County, Colorado
SANMIGUEL4	San Miguel River abv. Tabeguache Creek, Montrose County, Colorado

<u>Station</u>	<u>Latitude</u> <u>Degrees N</u>	<u>Longitude</u> <u>Degrees W</u>	<u>Elevation</u> <u>(meters)</u>	<u>Ecoregion</u>	<u>Comments</u>
SANMIGUEL1	38.01	108.05	2217	Southern Rockies	
SANMIGUEL2	38.11	108.19	2016	Southern Rockies	
SANMIGUEL3	38.25	108.39	1776	Southern Rockies	
SANMIGUEL4	38.34	108.70	1520	Southern Rockies	

Sampling Methods

Table 2. Sampling dates, methodology and comments. In station descriptor, QL = qualitative sample.

<u>Sample ID</u>	<u>Station</u>	<u>Date</u>	<u>Sampling</u> <u>Method</u>	<u>Habitat</u> <u>Sampled</u>	<u>Sampling</u> <u>Area (m2)</u>	<u>Comments</u>
112616	SANMIGUEL1	10/11/2000	SURBER	MULTIPLE	0.744	None
112617	SANMIGUEL2	10/11/2000	SURBER	MULTIPLE	0.744	None
112618	SANMIGUEL3	10/11/2000	SURBER	MULTIPLE	0.744	None
112619	SANMIGUEL4	10/11/2000	SURBER	MULTIPLE	0.744	None

Laboratory Methods

Samples were identified at the National Aquatic Monitoring Center, Logan, Utah. The basic procedures we followed for processing the samples are described in Cuffney et al. 1993 (Methods for collecting benthic invertebrate samples as part of the National Water-Quality Assessment Program. United States Geological Survey Open-File Report 93-406) and are described in greater detail and are rationalized in Vinson and Hawkins 1996 (Effects of sampling area and subsampling procedures on comparisons of taxa richness among streams. Journal of the North American Benthological Society 15:393-400).

If the sample appeared to contain more than 500 organisms, it was sub-sampled. Sub-samples were obtained by pouring the sample into an appropriate diameter 250 micron sieve, floating the material by placing the sieve within an enamel pan partially filled with water and leveling the material within the sieve. The sieve was then removed from the water pan and the material within the sieve was divided into equal parts. This process was repeated until it appeared that approximately 500 organisms remained in one-half of the sieve. This material was then placed little-by-little into a petri dish and all organisms were removed under a dissecting microscope at 10-60 power. Additional sub-samples were taken until at least 500 organisms were found. Once a sub-sample was started, all organisms within it were removed. The actual number of organisms removed from each sample is shown in Table 3. When the sorting of the sample splits was completed, the entire sample was spread throughout a large white enamel pan. The entire sample was then searched for 10 minutes to remove any taxa that might not have been picked up during the initial sample sorting process. The objective of this "big/rare" search was to provide a more complete taxa list by finding the rarer taxa that may have been excluded during the sub-sampling process. All the organisms removed during the sorting process were then identified by well-qualified taxonomists. An effort was made to identify organisms to a consistent taxonomic level. Insects were primarily identified to genus, with the exception of Chironomidae which were identified to subfamily. Non-insect invertebrates were identified to various taxonomic levels depending on the availability of identification keys. Voucher specimens were retained for all unique taxa. The identified portion of the sample was placed in 70% ethanol, given a unique catalog number, and will be kept forever, unless invertebrate dry weights were determined.

Table 3. Percentage of each sample processed and the number of invertebrates identified. In station descriptor, QL = qualitative sample.

Sample ID	Station	Date	Field split %	Lab split %	% id'd	Invertebrates identified	Comments
112616	SANMIGUEL1	10/11/2000	None	6	6	555	None
112617	SANMIGUEL2	10/11/2000	None	13	13	580	None
112618	SANMIGUEL3	10/11/2000	None	75	75	525	None
112619	SANMIGUEL4	10/11/2000	None	9	9	519	None

Data analysis and interpretation

This section is provided as an introduction to interpreting aquatic macroinvertebrate sample results. Additional information can be found in the resources cited at the end of this section. A variety of data measures have been developed to assess the stream health using aquatic macroinvertebrates. Those most commonly used are described below and have been calculated for your samples.

Benthic macroinvertebrates are important elements of water quality evaluations because they (1) live in, on, or near streambed sediments; (2) have relatively long life cycles; and (3) are relatively sessile compared with larger organisms, such as fish. This combination of characteristics ensures that benthic invertebrates (1) respond to natural and anthropogenic environmental conditions that physical or chemically alter streambed sediments; (2) integrate effects over a year; and (3) characterize effects over a relatively small spatial scale (in contrast with fish, which may travel long distances). These factors make benthic invertebrates well suited for use in assessing site-specific water quality and comparing spatial patterns of water quality at multiple sites, and for integrating effects up to a year after a pollution or disturbance event.

The occurrence of benthic invertebrates in a stream is a response to natural and anthropogenic influences. Rivers naturally change as they flow downstream. Riparian vegetation conditions, light, temperature, hydraulics, and substrate composition all change and in response to these environmental changes benthic invertebrate communities change. Thus, each location in a river has a range of environmental conditions that dictate which invertebrate species are found there.

Taxa richness - Richness is a component and estimate of community structure and stream health based on the number of distinct taxa. Taxa richness normally decreases with decreasing water quality. In some situations organic enrichment can cause an increase in the number of pollution tolerant taxa.

Abundance - The abundance, density, or number of aquatic macroinvertebrates per unit area is an indicator of habitat availability and fish food abundance. Abundance may be reduced or increased depending on the type of impact or pollutant. Increased organic enrichment typically causes large increases in abundance of pollution tolerant taxa. High flows, increases in fine sediment, or the presence of toxic substances normally cause a decrease in invertebrate abundance.

EPT - A summary of the taxa richness and abundance among the insect Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT). These orders are commonly considered sensitive to pollution.

Number of families - All families are separated and counted. The number of families normally decreases with decreasing water quality.

Percent taxon or family dominance - A community dominated by a single taxon or several taxa from the same family suggests environmental stress.

Shannon Diversity Index - Ecological diversity is a measure of community structure defined by the relationship between the number of distinct taxa and their relative abundances.

$$H = - \sum_{i=1}^S (p_i \ln p_i) \quad (1)$$

The Shannon index has been the most widely used in community ecology. The Shannon index was calculated as:

where H is the index of species diversity, S is the total number of taxa, and p_i is the proportional abundance of the i th species. The higher the number the greater the diversity. Another commonly used diversity index is Simpson's Index of diversity. The Simpson Index was calculated as:

$$D = 1 - \sum_{i=1}^S (p_i)^2 \quad (2)$$

where D is the Simpson index of diversity and p_i is the proportion of individuals of taxa i in the assemblage. Simpson's index gives little weight to the rare taxa and more weight to the common taxa. It ranges in value from 0 (low diversity) to a maximum of $(1 - 1/S)$, where S is the number of taxa.

Evenness - Evenness is a measure of the distribution of taxa within a community. The evenness index used in this report was calculated as:

$$Evenness = \frac{(1/\lambda) - 1}{(e^H) - 1} \quad (3)$$

where,

$$\lambda = \sum_{i=1}^S (p_i^2) \quad (4)$$

H is Shannon's diversity index (Equation 1) and S is the total number of taxa, and p_i is the proportional abundance of the i th species. Value ranges from 0-1 and approach zero as a single taxa becomes more dominant.

Biotic indices - Biotic indices use the indicator taxa concept. Taxa are assigned water quality tolerance values based on their specific tolerances to pollution. Scores are typically weighted by taxa relative abundance. In the United States the most common biotic indices in use are the Hilsenhoff Biotic Index and the USFS Biotic Condition Index that has been principally used by the Bureau of Land Management and the United States Forest Service.

Hilsenhoff Biotic Index - The Hilsenhoff Biotic Index (HBI) summarizes the overall pollution tolerances of the taxa collected. This index has been used to detect nutrient enrichment, high sediment loads, low dissolved oxygen, and thermal impacts. It is best at detecting organic pollution. Families were assigned an index value from 0- taxa normally found only in high quality unpolluted water, to 10- taxa found only in severely polluted waters. Index values came from Hilsenhoff (1987, 1988). A family level HBI was calculated as:

$$HBI = \sum (n_i t_i / N) \quad (5)$$

where n_i is the number of individuals of a taxon, t_i is the tolerance value of that taxon, and N is the total number of organisms in a sample. Samples with HBI values of 0-2 are considered clean, 2-4 slightly enriched, 4-7 enriched, and 7-10 polluted. Rather than using mean HBI values for a sample, taxon HBI values can also be used to determine the number of pollution intolerant and tolerant taxa occurring at a site. Taxa with HBI values of 0-2 are considered intolerant clean water taxa and taxa with HBI values of 9-10 are considered pollution tolerant taxa.

USFS Community tolerant quotient/biotic condition index - This index has been widely used by the USFS and BLM throughout the western United States. Taxa are assigned a tolerant quotient (TQ) from 2-taxa found only in high quality unpolluted water, to 108 - taxa

found in severely polluted waters. TQ values were developed by Winget and Mangum (1979). The community tolerance quotient (CTQa) was calculated as:

$$CTQa = \sum (TQ / S) \quad (6)$$

where TQ is the tolerance quotient of that taxon and S is the number of taxa in the sample. The dominance weighted community tolerance quotient (CTQd) was calculated as:

$$CTQd = \sum (n_i TQ / N) \quad (7)$$

where TQ is the tolerance quotient of that taxon, n_i is the number of individuals of a taxon, and N is the total number of organisms in the sample. If data on total alkalinity, sulfate, substrate size, and stream gradient was collected, the predicted community tolerance quotient (CTQp) was calculated. This is a prediction of the unimpacted benthic aquatic macroinvertebrate community structure based on these physical and chemical variables. If the CTQp was calculated, the biotic condition index (BCI) was calculated as:

$$BCI = \frac{CTQp}{CTQd} \times 100 \quad (8)$$

Invertebrate samples with BCIs >90 are considered to come from streams in excellent condition, 80-90 good condition, 72-79 fair condition, and <72 poor condition.

Functional feeding group measures - A useful classification scheme for aquatic macroinvertebrates is to categorize them by feeding acquisition mechanisms. Categories are based on food particle size and food location, e.g., suspended in the water column, deposited in sediments, leaf litter, or live prey. This classification system reflects the major source of the resource, either within the stream itself or from riparian or upland areas and the primary location, either erosional or depositional habitats. The character of a stream can be determined by evaluating the relative proportions of functional groups.

Shredders - Shredders use both living vascular hydrophytes and decomposing vascular plant tissue - coarse particulate organic matter (CPOM). Shredders are sensitive to changes in riparian vegetation. Shredders can be good indicators of toxicants that adhere to organic matter.

Scrapers - Scrapers feed on periphyton - attached algae and associated material. Scraper populations increase with increasing abundance of diatoms and can decrease as filamentous algae, mosses, and vascular plants increase. Scrapers decrease in relative abundance in response to sedimentation and organic pollution.

Collector-filterers - Collector-filterers feed on suspended fine particulate organic matter (FPOM). Collector-gatherers are sensitive to toxicants in the water column and deposited in sediments.

Collector-gatherers - Collector-filterers feed on deposited fine particulate organic matter. Collector-gatherers are sensitive to deposited toxicants.

Predators - Predators feed on living animal tissue.

Unknown feeding group - This category includes taxa that are highly variable, parasites, and those that for which the primary feeding mode is currently unknown.

Other measures - The number of long-lived taxa and the number of "clinger" taxa have been found by Karr and Chu (1998) to respond negatively to human disturbance. Clinger taxa were determined using information in Memitt and Cummins (1996). These taxa typically cling to the tops of rocks and are thought to be reduced by sedimentation or abundant algal growths. Long-lived taxa are those taxa that typically have 2-3 year life cycles. Disturbances and water quality and habitat impairment typically reduces the number of long-lived taxa.

Literature cited and additional information on sample interpretation

- Davis, W.S. and T.P. Simon, editors. 1995. Biological assessment and criteria: Tools for water resource planning and decision making. Lewis Publishers, Boca Raton, Florida.
- Elliott, J. M. 1971. Statistical analysis of benthic invertebrates. Scientific Publication No. 25 Freshwater Biological Association
- Hilsenhoff, W. L. 1988. Rapid field assessment of organic pollution with a family level biotic index. *The Journal of the North American Benthological Society*. 7:65-68.
- Hilsenhoff, W.L. 1987. An improved index of organic stream pollution. *The Great Lakes Entomologist*. 20:31-39.
- Karr, J.R. and E.W. Chu. 1998. Restoring life in running waters: better biological monitoring. Island Press, Washington, D.C.
- Lenat, D. R. 1988. Water quality assessment of streams using a qualitative collection method for benthic macroinvertebrates. *The Journal of the North American Benthological Society*. 7:222-233.
- Loeb, S.L and A. Spacie. 1994. Biological monitoring of aquatic systems. Lewis Publishers, Boca Raton, Florida.
- Magurran, A.E. 1988. Ecological diversity and its measurement. Princeton University Press.
- Merritt, R.W. and K.W. Cummins, editors, 1996. An introduction to the aquatic insects of North America. Kendall/Hunt Publishing Company, Dubuque, Iowa.
- Plafkin, J. L., M. T. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. U.S. Environmental Protection Agency, EPA/444/4-89-001.
- Resh, V. H. and D. M. Rosenberg (editors). 1993. Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman and Hall, New York.
- Wingett, R.N. and F. A. Mangum. 1979. Biotic condition index: integrated biological, physical, and chemical parameters for management. U.S. Forest Service Intermountain Region, U.S. Department of Agriculture, Ogden, UT.

Taxonomic identification resources used

- Brown, H. P. 1976. Aquatic Dryopoid Beetles (Coleoptera) of the United States. U. S. EPA. Cincinnati, Ohio. 82 Pages.
- Burch, J. B. 1973. Biota of Freshwater Ecosystems Identification Manual No. 11, Freshwater Unionacean Clams (Mollusca: Pelecypoda) of North America. U. S. Environmental Protection Agency, Project # 18050, Contract # 14-12-894. 176 Pages.
- Burch, J. B. 1973. Freshwater Unionacean Clams (Mollusca: gastropoda) of North America. U. S. Environmental Protection Agency, EPA-600/3-82-023. Contract # 68-03-1290. 193 Pages.
- Edmunds, G. F., Jr., S. L. Jensen and L. Berner. 1976. The Mayflies of North and Central America. North Central Publishing Co., St. Paul, Minnesota. 330 Pages.
- Johannsen, O. A. 1977. Aquatic Diptera: Eggs, Larvae, and Pupae of Aquatic Flies. Published by the University, Ithaca, New York. 210 Pages.
- Klemm, D. J. 1972. Biota of Freshwater Ecosystems Identification Manual No. 8, Freshwater Leeches (Annelida: Hirundinea) of North America. U.S. Environmental Protection Agency. Project # 18050, Contract # 14-12-894. 53 Pages.
- Klemm, D. J. 1985. A Guide to the Freshwater Annelida (Polychaeta, Naidid and Tubificid Oligochaeta and Hirudinea) of North America. Kendall/Hunt Publishing Co., Dubuque, Iowa. 198p.
- McCafferty, W. P. 1981. Aquatic Entomology. Jones and Bartlett Publishers, Inc., Boston. 448 Pages.
- Merritt, R. W. and K. W. Cummins (Editors). 1996. An Introduction to the Aquatic Insects of North America, Third Edition. Kendall/Hunt Publishing Co., Dubuque, Iowa. 862 Pages.
- Pennak, R. W. 1989. Freshwater Invertebrates of the United States, Third Edition, John Wiley and Sons, Inc, New York, 628 Pages.
- Stewart, K. W. and B. P. Stark. 1988. Nymphs of North American Stonefly Genera (Plecoptera). University of North Texas Press, Denton Texas. 460 Pages.
- Thorpe J. H. and A. P. Covich (Editors). 1991. Ecology and Classification of Freshwater Invertebrates. Academic Press, Inc., San Diego, California. 911 Pages.
- Wiederholm, T. (Editor) 1983. Chironomidae of the Holarctic Region. Entomologica Scandinavica. 457 Pages.
- Wiggins, G. B. 1996. Larvae of North American Caddisfly Genera (Tricoptera). Second Edition, University of Toronto Press. Toronto. 457 Pages.

Results

Abundance data is number per meter squared for quantitative samples and number per sample for qualitative samples. NC = Not calculated. * = unable to calculate. EPT = totals for the insect orders, Ephemeroptera, Plecoptera, Trichoptera. In station descriptor, QL = qualitative sample.

General Assemblage Measures

Station	Date	Sample ID	Total abundance	EPT abundance	# of families	Dominant family	Dom. Family abundance	Dom. Family % contribution
SANMIGUEL1	10/11/2000	112616	11149	9528	19	Baetidae	4531	40.64
SANMIGUEL2	10/11/2000	112617	5907	4621	22	Baetidae	1343	22.74
SANMIGUEL3	10/11/2000	112618	935	290	19	Chironomidae	353	37.75
SANMIGUEL4	10/11/2000	112619	7281	3364	16	Elmidae	3281	45.06
Mean			6318	4451	19		2377	37.62

Diversity Indices

Station	Date	Sample ID	Total taxa richness	EPT taxa richness	Shannon diversity	Simpson diversity	Evenness
SANMIGUEL1	10/11/2000	112616	30	18	1.897	0.253	0.521
SANMIGUEL2	10/11/2000	112617	36	22	2.544	0.117	0.646
SANMIGUEL3	10/11/2000	112618	28	12	2.455	0.118	0.704
SANMIGUEL4	10/11/2000	112619	26	11	2.195	0.168	0.621
Mean			30.0	15.8	2.273	0.164	0.623

Biotic Indices

Station	Date	Sample ID	Hilsenhoff Biotic Index		United States Forest Service Biotic Condition Index				
			Index	Indication	CTQp	CTQa	CTQd	BCI	Indication
SANMIGUEL1	10/11/2000	112616	2.64	Slight organic enrichment	51	50	52	98	Excellent
SANMIGUEL2	10/11/2000	112617	2.31	Slight organic enrichment	NC	52	57		
SANMIGUEL3	10/11/2000	112618	4.57	Moderate organic enrichment	NC	79	84		
SANMIGUEL4	10/11/2000	112619	4.06	Moderate organic enrichment	NC	90	91		
Mean			3.40		51	68	71		

Taxa richness and relative abundance by tolerance and intolerance to pollution based on Hilsenhoff Biotic Index (HBI). Intolerant taxa are those taxa given a HBI score of 0, 1, or 2. Tolerant taxa are those taxa given a HBI score of 8, 9, or 10. Data are expressed as the number of taxa or density per meter square meter for quantitative samples and number of taxa or density per sample for qualitative samples. Numbers in parentheses are percentages. In station descriptor, QL = qualitative sample.

Station	Date	Sample ID	Intolerant		Tolerant	
			Richness	Abundance	Richness	Abundance
SANMIGUEL1	10/11/2000	112616	10 (33)	840 (8)	0 (0)	0 (0)
SANMIGUEL2	10/11/2000	112617	15 (42)	2091 (35)	1 (3)	22 (0)
SANMIGUEL3	10/11/2000	112618	7 (25)	87 (9)	1 (4)	198 (21)
SANMIGUEL4	10/11/2000	112619	4 (15)	190 (3)	1 (4)	129 (2)
Mean			9	802	1	87

Functional feeding groups

Taxa richness by functional feeding group; number of taxa per meter squared for quantitative samples and number of taxa per sample for qualitative samples. Numbers in parentheses are percentages. In station descriptor, QL = qualitative sample.

Station	Date	Sample ID	Shredders	Scrapers	Collector filterers	Collector gatherers	Predators	Unknown
SANMIGUEL1	10/11/2000	112616	3 (10)	6 (20)	2 (7)	6 (20)	10 (33)	3 (10)
SANMIGUEL2	10/11/2000	112617	3 (8)	4 (11)	3 (8)	8 (22)	15 (42)	3 (8)
SANMIGUEL3	10/11/2000	112618	2 (7)	1 (4)	3 (11)	11 (39)	6 (21)	5 (18)
SANMIGUEL4	10/11/2000	112619	1 (4)	1 (4)	5 (19)	8 (31)	7 (27)	4 (15)
			-----	-----	-----	-----	-----	-----
Mean			2 (8)	3 (10)	3 (11)	8 (28)	10 (32)	4 (13)

Invertebrate abundance by functional feeding group; abundance per meter squared for quantitative samples and abundance per sample for qualitative samples. Numbers in parentheses are percentages. In station descriptor, QL = qualitative sample.

Station	Date	Sample ID	Shredders	Scrapers	Collector filterers	Collector gatherers	Predators	Unknown
SANMIGUEL1	10/11/2000	112616	3294 (30)	413 (4)	445 (4)	6362 (57)	399 (4)	237 (2)
SANMIGUEL2	10/11/2000	112617	1059 (18)	269 (5)	1167 (20)	2859 (48)	478 (8)	75 (1)
SANMIGUEL3	10/11/2000	112618	23 (2)	92 (10)	7 (1)	491 (53)	229 (24)	93 (10)
SANMIGUEL4	10/11/2000	112619	14 (0)	30 (0)	2344 (32)	4413 (61)	334 (5)	146 (2)
			-----	-----	-----	-----	-----	-----
Mean			1098 (17)	201 (3)	991 (16)	3531 (56)	360 (6)	138 (2)

The 10 metrics thought to be most responsive to human-induced disturbance (Karr and Chu 1998).

Station	Date	Sample ID	Ephemeroptera		Long-lived		Intolerant	%	Clinger	% contribution		
			Total taxa	Plecoptera taxa	Trichoptera taxa	taxa				dominant taxon	% predators	
SANMIGUEL1	10/11/2000	112616	30	5	7	6	4	10	0.0	13	40.6	3.6
SANMIGUEL2	10/11/2000	112617	36	5	9	8	7	15	0.4	19	22.7	8.1
SANMIGUEL3	10/11/2000	112618	28	5	4	3	8	7	21.2	11	21.2	24.5
SANMIGUEL4	10/11/2000	112619	26	3	3	5	5	4	1.8	11	31.1	4.6
Mean			30	5	6	6	6	9	1.4	14	33.0	5.7

Aquatic macroinvertebrate community summary statistics for all samples analyzed from the Southern Rockies ecoregion. Summary is based on 577 samples taken at 408 different sampling stations. Dominant family (%) is the percentage of samples in which that family was most numerically abundant. *** = unable to calculate or < 0.1. SD = standard deviation. Summaries are based on both fixed area and qualitative samples.

Assemblage summary metrics	Maximum	Minimum	Mean	SD
Total number of taxa:	42	1	20.0	8.6
Number of EPT taxa:	28	0	11.6	5.5
Sample abundance:	71953	3	4116.9	6702.9
EPT abundance:	48387	0	2332.5	4367.3
Number of families:	26	0	13.1	4.8
Dominant families: Chironomidae (29%), Heptageniidae (19%), Baetidae (12%)				
Contribution of dominant family:	39.6%	100.0%	43.9%	
Contribution of dominant taxon:	36.0%	66.7%	39.8%	
Shannon diversity:	3.12	0.00	2.06	0.6
Simpson diversity:	1.00	0.05	0.22	0.1
Margalef diversity:	6.56	0.00	2.57	1.1
Menhinick diversity:	2.68	0.08	0.56	0.4
Hill's Evenness:	0.99	0.00	0.63	0.1
Number of clinger taxa:	23	0	8.2	4.4
Number of long-lived taxa:	9	0	2.3	2.0

Biotic Indices

Hilsenhoff Biotic Condition Index:	7.0	0.0	3.4	1.0
Number of intolerant taxa (HBI <=2):	17	0	6.5	3.5
Intolerant taxa abundance:	27054	0	1091.4	2622.1
Number of tolerant taxa (HBI >=8):	2	0	0.7	0.5
Tolerant taxa abundance:	25892	0	274.0	1493.0
USFS Community Tolerance Quotient, CTQd:	108	12	65	14.6

Major taxonomic groups

Group	Taxonomic richness				Abundance	
	Maximum	Minimum	Mean	Mean %	Mean	Mean %
Ephemeroptera:	12	0	4.3	21.3	1528	37.1
Plecoptera:	11	0	4.0	20.1	340	8.3
Trichoptera:	10	0	3.3	16.3	464	11.3
Coleoptera:	6	0	1.4	6.9	245	6.0
Megaloptera:	1	0	<0.1	<0.1	<1	<0.1
Diptera:	12	0	5.2	25.8	1285	31.2
Chironomidae:	4	0	2.2	11.1	1020	24.8
Crustacea:	3	0	0.3	1.3	46	1.1
Oligochaeta:	2	0	0.4	1.9	53	1.3
Mollusca:	3	0	0.1	0.6	4	0.1

Functional feeding groups

Group	Taxonomic richness				Abundance	
	Maximum	Minimum	Mean	Mean %	Mean	Mean %
Shredders:	7	0	2.2	11.0	238	5.8
Scrapers:	8	0	2.8	13.8	474	11.5
Collector-filterers:	7	0	2.2	10.8	417	10.1
Collector-gatherers:	13	0	5.9	29.3	2449	59.5
Predators:	15	0	5.0	24.9	375	9.1

List of taxa collected in 4 samples at sites listed in Table 1. Abundance data is number per meter squared.

<u>Order</u>	<u>Family</u>	<u>Subfamily/Genus/species</u>	<u>Average abundance</u>
Phylum: Arthropoda			
Class: Arachnida			
Trombidiformes			68.10
Class: Insecta			
Coleoptera	Dryopidae	Helichus	0.45
Coleoptera	Elmidae		431.32
Coleoptera	Elmidae	Microcylloepus	566.90
Coleoptera	Elmidae	Optioservus	63.40
Coleoptera	Elmidae	Zaitzevia	35.84
Diptera			24.64
Diptera	Atherceridae	Atherix	36.29
Diptera	Blephariceridae	Bibiocephala	8.74
Diptera	Chironomidae	Chironominae	87.13
Diptera	Chironomidae	Orthoclaadiinae	339.93
Diptera	Chironomidae	Tanytopdinae	56.78
Diptera	Empididae		3.58
Diptera	Empididae	Chelifera	11.65
Diptera	Empididae	Hemerodromia	10.75
Diptera	Empididae	Trichoclinocera	10.75
Diptera	Simuliidae		28.66
Diptera	Simuliidae	Simulium	4.03
Diptera	Tipulidae		0.90
Diptera	Tipulidae	Antocha	16.13
Diptera	Tipulidae	Dicranota	5.71
Diptera	Tipulidae	Hexatoma	19.71
Ephemeroptera	Baetidae	Baetis	1493.49
Ephemeroptera	Ephemerellidae		176.96
Ephemeroptera	Ephemerellidae	Drunella doddsi	16.47
Ephemeroptera	Ephemerellidae	Drunella grandis	2.69
Ephemeroptera	Heptageniidae		10.75
Ephemeroptera	Heptageniidae	Epeorus	5.38
Ephemeroptera	Heptageniidae	Rhithrogena	164.76
Ephemeroptera	Leptophlebiidae		9.41
Ephemeroptera	Tricorythidae	Tricorythodes	211.83
Lepidoptera	Pyratidae	Petrophila	7.50
Odonata	Gomphidae		0.45
Odonata	Gomphidae	Ophiogomphus	0.34
Plecoptera			38.53
Plecoptera	Capniidae		126.57
Plecoptera	Chloroperlidae		29.57
Plecoptera	Chloroperlidae	Sweltsa	26.88
Plecoptera	Perlidae		5.38
Plecoptera	Perlidae	Claassenia	1.68
Plecoptera	Perlidae	Doroneuria	26.64
Plecoptera	Perlodidae		14.34
Plecoptera	Perlodidae	Isogenoides	2.35
Plecoptera	Perlodidae	Isoperla	10.75
Plecoptera	Pteronarcidae	Pteronarcella	19.49
Trichoptera	Brachycentridae	Brachycentrus	299.73
Trichoptera	Glossosomatidae	Glossosoma	34.95
Trichoptera	Hydropsychidae		71.98
Trichoptera	Hydropsychidae	Arctopsyche	40.66
Trichoptera	Hydropsychidae	Cheumatopsyche	151.13
Trichoptera	Hydropsychidae	Hydropsyche	394.31
Trichoptera	Hydroptilidae	Hydroptila	3.58
Trichoptera	Lepidostomatidae	Lepidostoma	947.25
Trichoptera	Leptoceridae	Oecetis	45.68
Trichoptera	Rhyacophilidae	Rhyacophila	8.40
Trichoptera	Uenoidae	Oligophlebodes	59.14
Phylum: Mollusca			
Class: Gastropoda			
Basommatophora	Lymnaeidae		0.45
Basommatophora	Physidae	Physella	27.44
A total of 58 taxa were collected in 4 samples.			6318.24

Relative contribution of taxon collected from all listed in Table 1. Abundance data is number per meter squared for quantitative samples and number per sample for qualitative samples. ***,* = <0.1%.

<u>Taxon</u>	<u>Average abundance</u>	<u>Average percent</u>	<u>Cumulative percent</u>
Baetis	1493	23.6	23.6
Lepidostoma	947	15.0	38.6
Microcylloepus	567	9.0	47.6
Elmidae	431	6.8	54.4
Hydropsyche	394	6.2	60.7
<u>Five dominant taxa</u>			
Orthocladiinae	340	5.4	66.0
Brachycentrus	300	4.7	70.8
Tricorythodes	212	3.4	74.1
Ephemerellidae	177	2.8	76.9
Rhithrogena	165	2.6	79.6
<u>Ten dominant taxa</u>			
Cheumatopsyche	151	2.4	81.9
Capniidae	127	2.0	84.0
Chironominae	87	1.4	85.3
Hydropsychidae	72	1.1	86.5
Trombidiformes	68	1.1	87.5
Optioservus	63	1.0	88.5
Oligophlebodes	59	0.9	89.5
Tanypodinae	57	0.9	90.4
Oecetis	46	0.7	91.1
Arctopsyche	41	0.6	91.8
Plecoptera	39	0.6	92.4
Atherix	36	0.6	92.9
Zaitzevia	36	0.6	93.5
Glossosoma	35	0.6	94.1
Chloroperlidae	30	0.5	94.5
Simuliidae	29	0.5	95.0
Physella	27	0.4	95.4
Sweltsa	27	0.4	95.8
Doroneuria	27	0.4	96.3
Diptera	25	0.4	96.6
Hexatoma	20	0.3	97.0
Pteronarcella	19	0.3	97.3
Drunella doddsi	16	0.3	97.5
Antocha	16	0.3	97.8
Perlodidae	14	0.2	98.0
Chelifera	12	0.2	98.2
Trichoclinocera	11	0.2	98.4
Isoperla	11	0.2	98.5
Heptageniidae	11	0.2	98.7
Hemerodromia	11	0.2	98.9
Leptophlebiidae	9	0.1	99.0
Bibliocephala	9	0.1	99.2
Rhyacophila	8	0.1	99.3
Petrophila	8	0.1	99.4
Dicranota	6	0.1	99.5

Relative taxon contribution table continued.

<u>Taxon</u>	<u>Average Abundance</u>	<u>Average Percent</u>	<u>Cumulative Percent</u>
Epeorus	5	0.1	99.6
Perlidae	5	0.1	99.7
Simulium	4	0.1	99.7
Empididae	4	0.1	99.8
Hydroptila	4	0.1	99.9
Drunella grandis	3	***.*	99.9
Isogenoides	2	***.*	99.9
Claassenia	2	***.*	100.0
Tipulidae	1	***.*	100.0
Helichus	1	***.*	100.0
Gomphidae	1	***.*	100.0
Lymnaeidae	1	***.*	100.0
Ophiogomphus	1	***.*	100.0

A total of 58 taxa were collected in 4 samples.

Ecological, pollution tolerance, and distribution data for the invertebrates collected.

Taxon	Functional Feeding Group	HBI	USFS TQ	Habitat	Distribution
Trombidiformes	PR	11	98	Lotic/lentic, benthic, vegetation	widespread
Helichus	UN	5	72	Lotic-erosional	Widespread
Elmidae	CG	4	104	Generally lotic and lentic-erosional, few lentic vascular hydrophytes	widespread
Microcylloepus	CG	4	104	Lotic-erosional and depositional	Widespread
Optioservus	SC	4	104	Lotic-erosional and depositional	Widespread
Zaitzevia	UN	4	104	Lotic-erosional	West
Diptera	UN	11	72	various	widespread
Atherix	PR	11	66	Lotic-erosional and depositional	Widespread
Bibiocephala	SC	0	2	Lotic-erosional	West mountains
Chironominae	CG	8	108	unknown	widespread
Orthoclaudiinae	CG	6	108	unknown	widespread
Tanypodinae	PR	6	108	unknown	widespread
Empididae	PR	6	95	Lotic-erosional and depositional, lentic-littoral	widespread
Chelifera	UN	6	95	Lotic-depositional, lentic-littoral	Widespread
Hemerodromia	PR	6	95	Lotic-erosional and depositional	Widespread
Trichoclinocera	PR	6	95	Lotic-erosional	Widespread
Simuliidae	CF	6	108	Lotic-erosional	widespread
Simulium	CF	6	108	Lotic and lentic erosional	Widespread
Tipulidae	SH	3	72	Lentic-littoral, lotic-erosional and depositional	Widespread
Antocha	CG	3	40	Lotic-erosional	Widespread
Dicranota	PR	3	36	Lotic-erosional and depositional, lentic-littoral, lotic & lentic margins	Widespread
Hexatoma	PR	3	36	Lotic-erosional and depositional, lentic-littoral	Widespread
Baetis	CG	4	72	Lotic-erosional and depositional, lentic-littoral, vascular hydrophytes	Widespread
Ephemerellidae	CG	1	48	Lotic-erosional, some depositional, macrophytes,	Widespread
Drunella doddsi	SC	1	2	unknown	Widespread
Drunella grandis	PR	1	2	unknown	widespread
Heptageniidae	SC	4	48	Generally lotic and lentic-erosional	widespread
Epeorus	CG	4	18	Lotic-erosional	Widespread
Rhythrogena	CG	4	21	Lotic-erosional	Widespread
Leptophlebiidae	CG	2	36	Generally lotic-erosional	widespread
Tricorythodes	CG	4	108	Lotic-depositional, lentic-littoral	Widespread
Petrophila	SC	5	72	Lotic-erosional, lentic-erosional	Widespread
Gomphidae	PR	1	108	Lotic-depositional, lentic-littoral	widespread
Ophiogomphus	PR	1	108	Lotic-erosional and depositional of small cold streams	Widespread(partic. mountains and High Lat.)
Plecoptera	UN	11	108	various	widespread
Capniidae	SH	1	32	Lotic-erosional and depositional	widespread
Chloroperlidae	PR	1	24	Generally lotic-erosional	widespread
Sweltsa	PR	1	24	unknown	East, West
Perlidae	PR	1	24	Generally lotic and lentic-erosional	widespread
Claassenia	PR	1	6	unknown	West, North
Doroneuria	UN	1	18	unknown	West
Perlodidae	PR	2	48	Generally lotic and lentic-erosional	widespread
Isogenoides	PR	2	30	Lotic-erosional and depositional	East, North, West
Isoperla	PR	2	48	Lotic-erosional and depositional, large cold lake	Widespread
Pteronarcella	SH	11	30	Lotic-erosional and depositional	West, Southwest
Brachycentrus	CF	1	54	Lotic-erosional	Widespread
Glossosoma	SC	0	24	Lotic-erosional	Widespread
Hydropsychidae	CF	4	108	Lotic-erosional, some lentic-erosional	widespread
Arctopsyche	CF	4	18	Lotic-erosional	Widespread
Cheumatopsyche	CF	4	108	Lotic-erosional	Widespread
Hydropsyche	CF	4	108	Lotic-erosional	Widespread
Hydroptila	PH	4	108	Lotic-erosional and depositional	Widespread

Taxa information table, continued.

<u>Taxon</u>	<u>Functional Feeding Group</u>	<u>MBI</u>	<u>USFS TQ</u>	<u>Habitat</u>	<u>Distribution</u>
Lepidostoma	SH	11	24	Lotic-erosional and depositional	Widespread
Oecetis	PR	4	54	Lotic-erosional and depositional, lentic-littoral	Widespread
Rhyacophila	PR	0	30	Lotic-erosional	Widespread (except Great Plains)
Oligophlebodes	SC	11	30	unknown	West / Nearctic
Lymnaeidae	CG	11	108	various	widespread
Physella	CG	11	108	unknown	widespread

MBI - Hilsenhoff Biotic Index (Hilsenhoff 1987)

USFS TQ - Pollution tolerance quotient (Mangum 1979)

Functional feeding groups: CG - collector gatherers, CF - collector filterers, SC - scrapers, SH - shredders, PA - parasites, PR - predators, UN - unknown or highly variable, XY - xylophages (wood eaters)

Taxa Lists For Individual Samples

Taxonomic list and abundances of aquatic invertebrates collected 10/11/2000 at station SANMIGUEL1, San Miguel River above Placerville, Colorado. Sample identification number is 112616. Life stage: L = Larve, P = pupae, A = adult. NC = not calculated. Abundance data is presented as number per meter squared.

<u>Order</u>	<u>Family</u>	<u>Subfamily/Genus/species</u>	<u>Life Stage</u>	<u>multiple habitat abundance</u>
Phylum: Arthropoda				
Class: Arachnida				
Trombidiformes			A	129
Class: Insecta				
Coleoptera	Elmidae		L	129
Coleoptera	Elmidae	Optioservus	A	22
Diptera			L	86
Diptera	Atherceridae	Atherix	L	44
Diptera	Blephariceridae	Bibiocephala	L	24
Diptera	Chironomidae	Orthocladiinae	L	1055
Diptera	Chironomidae	Tanypodinae	L	43
Diptera	Empididae	Chelifera	L	22
Diptera	Tipulidae	Antocha	L	43
Diptera	Tipulidae	Dicranota	L	22
Diptera	Tipulidae	Hexatoma	L	3
Ephemeroptera	Baetidae	Baetis	L	4531
Ephemeroptera	Ephemerellidae	Drunella doddsi	L	66
Ephemeroptera	Heptageniidae		L	43
Ephemeroptera	Heptageniidae	Epeorus	L	22
Ephemeroptera	Heptageniidae	Rhithrogena	L	582
Plecoptera			L	129
Plecoptera	Capniidae		L	196
Plecoptera	Chloroperlidae		L	22
Plecoptera	Chloroperlidae	Sweltsa	L	86
Plecoptera	Perlodidae		L	22
Plecoptera	Perlodidae	Isogenoides	L	8
Plecoptera	Pteronarcidae	Pteronarcella	L	66
Trichoptera	Brachycentridae	Brachycentrus	L	352
Trichoptera	Glossosomatidae	Glossosoma	L	43
Trichoptera	Hydropsychidae	Arctopsyche	L	93
Trichoptera	Lepidostomatidae	Lepidostoma	L	3032
Trichoptera	Rhyacophilidae	Rhyacophila	L	22
Trichoptera	Uenoidae	Oligophlebodes	L	215

Total:	30 taxa			11149

Taxonomic list and abundances of aquatic invertebrates collected 10/11/2000 at station SANMIGUEL2, San Miguel River below Beaver Creek, Colorado. Sample identification number is 112617. Life stage: L = Larve, P = pupae, A = adult. NC = not calculated. Abundance data is presented as number per meter squared.

<u>Order</u>	<u>Family</u>	<u>Subfamily/Genus/species</u>	<u>Life Stage</u>	<u>multiple habitat abundance</u>
Phylum: Arthropoda				
Class: Arachnida				
Trombidiformes			A	140
Class: Insecta				
Coleoptera	Elmidae		L	570
Coleoptera	Elmidae	Optioservus	L	129
Coleoptera	Elmidae	Optioservus	A	11
Coleoptera	Elmidae	Zaitzevia	L	54
Diptera			P	11
Diptera	Atherceridae	Atherix	L	101
Diptera	Blephariceridae	Bibiocephala	L	11
Diptera	Chironomidae	Chironominae	L	22
Diptera	Chironomidae	Orthoclaadiinae	L	161
Diptera	Empididae	Trichoclinocera	L	43
Diptera	Empididae	Chelifera	L	11
Diptera	Tipulidae	Antocha	L	22
Diptera	Tipulidae	Dicranota	L	1
Diptera	Tipulidae	Hexatoma	L	1
Ephemeroptera	Baetidae	Baetis	L	1343
Ephemeroptera	Ephemerellidae		L	634
Ephemeroptera	Ephemerellidae	Drunella grandis	L	11
Ephemeroptera	Heptageniidae	Rhithrogena	L	75
Ephemeroptera	Leptophlebiidae		L	32
Plecoptera	Capniidae		L	290
Plecoptera	Chloroperlidae		L	43
Plecoptera	Chloroperlidae	Sweltsa	L	22
Plecoptera	Perlidae		L	22
Plecoptera	Perlidae	Claassenia	L	7
Plecoptera	Perlodidae		L	22
Plecoptera	Perlodidae	Isogenoides	L	1
Plecoptera	Perlodidae	Isoperla	L	43
Plecoptera	Pteronarcidae	Pteronarcella	L	12
Trichoptera	Brachycentridae	Brachycentrus	L	845
Trichoptera	Glossosomatidae	Glossosoma	L	97
Trichoptera	Hydropsychidae	Arctopsyche	L	70
Trichoptera	Hydropsychidae	Hydropsyche	L	251
Trichoptera	Lepidostomatidae	Lepidostoma	L	757
Trichoptera	Leptoceridae	Oecetis	L	11
Trichoptera	Rhyacophilidae	Rhyacophila	L	12
Trichoptera	Uenoidae	Oligophlebodes	L	22

Total:	36 taxa			5907

Taxonomic list and abundances of aquatic invertebrates collected 10/11/2000 at station SANMIGUEL3, San Miguel River abv. Pinon, belw CC ditch, Colorado. Sample identification number is 112618. Life stage: L = Larve, P = pupae, A = adult. NC = not calculated. Abundance data is presented as number per meter squared.

<u>Order</u>	<u>family</u>	<u>Subfamily/Genus/species</u>	<u>Life Stage</u>	<u>multiple habitat abundance</u>
Phylum: Arthropoda				
Class: Arachnida				
Trombidiformes			A	4
Class: Insecta				
Coleoptera	Dryopidae	Helichus	A	2
Coleoptera	Elmidae		L	23
Coleoptera	Elmidae	Microcyloepus	L	4
Coleoptera	Elmidae	Optioservus	L	92
Coleoptera	Elmidae	Zaitzevia	L	73
Coleoptera	Elmidae	Zaitzevia	A	2
Diptera			P	2
Diptera	Chironomidae	Chironominae	L	198
Diptera	Chironomidae	Orthoclaadiinae	L	29
Diptera	Chironomidae	Tanypodinae	L	127
Diptera	Simuliidae	Simulium	L	2
Diptera	Tipulidae		L	4
Diptera	Tipulidae	Hexasoma	L	29
Ephemeroptera	Baetidae	Baetis	L	14
Ephemeroptera	Ephemerellidae		L	2
Ephemeroptera	Heptageniidae	Rhithrogena	L	2
Ephemeroptera	Leptophlebiidae		L	5
Ephemeroptera	Tricorythidae	Tricorythodes	L	160
Odonata	Gomphidae		L	2
Plecoptera			L	11
Plecoptera	Capniidae		L	20
Plecoptera	Chloroperlidae		L	54
Plecoptera	Perlidae	Doroneuria	L	4
Trichoptera	Brachycentridae	Brachycentrus	L	1
Trichoptera	Hydropsychidae	Hydropsyche	L	4
Trichoptera	Leptoceridae	Oecetis	L	14
Phylum: Mollusca				
Class: Gastropoda				
Basommatophora	Lymnaeidae		A	2
Basommatophora	Physidae	Physella	A	52

Total: 28 taxa				935

Taxonomic list and abundances of aquatic invertebrates collected 10/11/2000 at station SANMIGUEL4, San Miguel River abv. Tabeguache Creek, Colorado. Sample identification number is 112619. Life stage: L = Larve, P = pupae, A = adult. NC = not calculated. Abundance data is presented as number per meter squared.

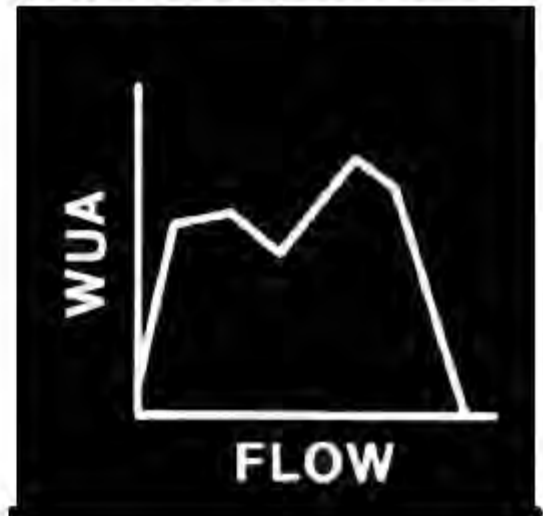
<u>Order</u>	<u>Family</u>	<u>Subfamily/Genus/species</u>	<u>Life Stage</u>	<u>multiple habitat abundance</u>
Phylum: Arthropoda				
Class: Insecta				
Coleoptera	Elmidae		L	1003
Coleoptera	Elmidae	Microcylloepus	L	2207
Coleoptera	Elmidae	Microcylloepus	A	57
Coleoptera	Elmidae	Zaitzevia	L	14
Diptera	Chironomidae	Chironominae	L	129
Diptera	Chironomidae	Orthocladiinae	L	115
Diptera	Chironomidae	Tanypodinae	L	57
Diptera	Empididae		L	14
Diptera	Empididae	Chelifera	L	14
Diptera	Empididae	Hemerodromia	L	43
Diptera	Simuliidae		L	115
Diptera	Simuliidae	Simulium	L	14
Diptera	Tipulidae	Hexatoma	L	46
Ephemeroptera	Baetidae	Baetis	L	86
Ephemeroptera	Ephemerellidae		L	72
Ephemeroptera	Tricorythidae	Tricorythodes	L	688
Lepidoptera	Pyratidae	Petrophila	L	30
Odonata	Gomphidae	Ophiogomphus	L	1
Plecoptera			L	14
Plecoptera	Perlidae	Doroneuria	L	103
Plecoptera	Perlodidae		L	14
Trichoptera	Hydropsychidae		L	288
Trichoptera	Hydropsychidae	Cheumatopsyche	L	605
Trichoptera	Hydropsychidae	Hydropsyche	L	1322
Trichoptera	Hydroptilidae	Hydroptila	L	14
Trichoptera	Leptoceridae	Oecetis	L	158
Phylum: Mollusca				
Class: Gastropoda				
Basommatophora	Physidae	Physella	A	57
Total: 26 taxa				----- 7281

APPENDIX – E



PHABSIM for Windows

User's Manual and
Exercises
Midcontinent Ecological
Science Center
November 2001
Open File Report 01-340



U.S. Department of the
Interior
U.S. Geological Survey



Acknowledgments

This document evolved from IF310 course materials developed and revised numerous times since 1984. Several individuals made significant contributions to the Windows } version of the software and this version of the manual in the following order. All are employees of the Midcontinent Ecological Science Center (MESC), U.S. Geological Survey (USGS), unless otherwise noted. Mr. John Bartholow wrote early versions of the laboratory exercises. Mr. Ken Bovee provided revision and insight to habitat suitability curve development and testing. Dr. Robert Milhous wrote the original PHABSIM programs. He also wrote the PHABSIM Version 2 (DOS) reference manual with assistance from Ms. Marlys Updike and Ms. Dianne Schneider (Milhous et al., 1989). Substantial portions of this text and of the Version 2 class text were taken or adapted from that earlier work. Dr. Thomas Hardy, Utah State University, consolidated and expanded on earlier course materials to provide a working draft of the PHABSIM Version 2 (DOS) class text under contract to the MESC. Substantial portions of the text in this document (in all chapters and in the laboratory exercises) are adapted from that draft. Dr. Sam Williamson contributed numerous insights into the techniques and strategy of habitat modeling and wrote the descriptive text for those ideas. Mr. Jeff Sandelin designed and programmed the Windows } interface and made numerous contributions to the text while employed under a support services contract. Ms. Julianne Brown, also a support services contractor, performed extensive testing of the programs to ensure results were correct and congruent with the previous version of the software. Mr. Jim Henriksen provided numerous insightful review comments and text revisions while using the PHABSIM for Windows programs. Dr. Terry Waddle supervised the design and testing of this software version. He also contributed substantial new text material while editing this version of the manual and laboratory exercises to reflect the overarching IFIM concept and the PHABSIM for Windows structure.

Preface

A Brief History of PHABSIM

In the 1970's a major change in terminology regarding maintaining streamflow to protect aquatic organisms in streams was introduced. To some, the change was considered merely semantic. But to those whose pioneering work led to the change, it was both substantive and significant. The change was from common usage of the term "low flow" or "minimum flow" to the common usage of the term "instream flow." During the early 1970's, the *Water Resources Research Catalog* served as an index of most of the ongoing research related to water resources, with each project identified by several key words. As late as 1975, the *Catalog* contained no research projects under the key words "instream flow," while at the same time, there were many studies using the key words "low flow."

The typical description of the concept of "low flow" in those days was something like this:

"Water is taken out of the stream for a variety of uses, such as irrigated agriculture, municipal and industrial. Low flow means that amount of water that must be left in the stream for the fish. With anything less than the low flow, the fish will die."

In a thoughtful piece published in the April 1991 edition of *Rivers*, Harvey Doerksen recalled how Don Tenant, then an aquatic biologist for the State of Montana, described the shortcomings of the "low flow" concept in human terms:

After many years, I still have a vivid recollection of a photographic slide that [Don Tennant] showed as part of his presentation at a conference. It was a picture of a family of perhaps half a dozen people crowded into a small bathroom. ... The point that Don wished to make was simply this: in the short run, a population of fish in the stream can make out quite well with an extreme low flow event, just as a family can tolerate the closeness that comes with crowding into a small bathroom. Over extended periods, however, the low flow could not be tolerated any better by a population of fish than sustained proximity could be tolerated by a family in a crowded bathroom. And yet, that very concept of maintaining a sustained low residual flow was the prevailing approach to protecting fish habitat.

One of the serious problems with the "low flow" approach was that biologists distinguished only between two relative conditions with respect to fish habitats: the level below which disaster would occur, and everything else. However, other water users made incremental assessments of their need. An irrigation district, for example, could project water quantity needs for any increment of irrigated acreage, but the biologists at the time did not have the technology to do similar incremental assessments of the potential impacts of various irrigated acreage scenarios.

In the late 1970's the U.S. Fish and Wildlife Service (FWS), through what then was its Office of Biological Services, received funding from the Environmental Protection Agency (EPA) to establish the Cooperative Instream Flow Service Group, which incorporated the combined talents of people from several federal and state agencies. The Group's central charge was to develop methods for quantifying the biological effects of altered streamflows.

The result of a concerted effort on the part of the Instream Flow Group was the Instream Flow Incremental Methodology (IFIM) (Stalnaker et al., 1995; Bovee et al., 1998), of which the Physical Habitat Simulation System (PHABSIM) is a major component. This new technology was highly significant for at least two reasons. First, it allowed fishery biologists to *negotiate* acceptable flow levels with other instream and out-of-stream water users *from among a variety of possible scenarios*, in the same way that the other users had been doing for years.

Second, the change in the prevailing terminology from “low flow” to “instream flow use” meant that biologists no longer were trying to find that magical flow level below which a stream should not be dewatered. Instead, they were in a position to assert instream flow *needs* for fish habitats and other environmental values. Furthermore, they could do so in terms of the seasonal life cycle needs of the fish (or other aquatic organisms) over the annual hydrograph. This change was thus an instrument through which fish and associated environmental values were viewed as legitimate water users among many, instead of merely a residual, after the water users had been served.

This change was not easy, nor did it occur overnight. In developing PHABSIM, the Instream Flow Group drew on several developments in instream habitat assessment that were available at the time. Two developments were of particular importance, the Washington Method (Collings et al., 1972) and the univariate curve concept. The Washington Method provided the concept of mapping depth and velocity conditions over gravel bars and applying binary suitability functions for salmon spawning in streams in the Pacific Northwest. The area of a gravel bar suitable for spawning was evaluated at several measured discharges by calculating the area having a suitability value of 1 for both depth and velocity. Approximate suitable spawning area for unmeasured intermediate flows was estimated by interpolation.

Binary suitability functions (the observed condition is assigned a value of 0 or 1, unsuitable or suitable) produced a value of 0 for some stream areas that, although not optimally suitable, were observed being used by salmon. The use of a univariate suitability function, which ranked various depths or rates of flow velocity on a 0 to 1 scale and allowed a smooth function covering the entire range of conditions, was proposed by Waters (1976).

The Washington Method, even when modified to include the univariate curve approach, requires numerous empirical measurements at different discharges. This limits the number of discharges for which habitat can be evaluated and the number of study areas that can feasibly be evaluated with time, manpower, and budget constraints.

The Instream Flow Group combined standard one-dimensional hydraulic simulation techniques with the Washington Method and the univariate curve concept to produce PHABSIM. PHABSIM uses the hydraulic simulation models to predict depth and velocity at unmeasured flows using basic physical and engineering principles that were standard practice in the 1970's. The resulting software suite multiplied surface area for a section of stream by the univariate suitability curve values for depth, velocity, and channel condition to arrive at a habitat index called Weighted Usable Area.

This software suite was first implemented on Control Data Corporation mainframe computers accessed by terminals connected over telephone lines. The software consisted of numerous small piecemeal programs that were cost-effective to develop and use in the mainframe environment. Numerous small files were required for data input and numerous output files were produced. This placed a major burden on users of the software to manage large numbers of files with often similar (but slightly different) contents. It also produced a legacy of program names such as IFG-4.

During 1984 and 1985 the PHABSIM program suite was moved to microcomputers. A basic menu-driven interface for the PHABSIM program was developed in 1989. The PHABSIM Version 2 (DOS) (Milhous et al., 1989) programs were distributed until September 2000 as the standard version of PHABSIM software.

With the advent of the Windows graphical user interface, it became evident that the PHABSIM program suite would serve a wider audience if input data and model results could be displayed graphically during an application of the software. Development of the Windows interface for PHABSIM fulfills commitments made to the U.S. Fish and Wildlife Service in the mid-1990's. Two principle goals were pursued while developing PHABSIM for Windows: (1) to keep the functionality of all core programs and retain backward compatibility to PHABSIM Version 2, and (2) to simplify the bookkeeping and calibration processes. We sought to both improve clarity of the various options for each program and graphically display the results of applying each program. The ability to view plots of model results during the calibration and option selection processes greatly speeds up calibration and increases understanding of the effects of selecting various habitat simulation options.

To ensure the quality of PHABSIM for Windows, extensive testing and comparison with the DOS-based PHABSIM Version 2 was performed. Several data sets were run through both versions and all options of all programs were run and compared. In addition, both English and metric units were tested to ensure that entire analyses could be reliably conducted in metric units. Our emphasis was on retaining the full set of PHABSIM analytical functions and extensively testing the programs rather than on adding program enhancements.

Use of This Document

This document is a combined self-study textbook and reference manual. The material is presented in the general order of a PHABSIM study placed within the context of an IFIM application. The document may also be used as reading material for a lecture-based course. This manual provides documentation of the various PHABSIM programs so every option of each program is treated.

This text is not a guidebook for organization and implementation of a PHABSIM study. Use of PHABSIM should take place in the context of an IFIM application. See Bovee et al. (1998) for guidance in designing and performing a PHABSIM study as part of a larger IFIM application.

The document concludes with a set of 12 laboratory exercises. Users are strongly encouraged to work through the laboratory exercises prior to applying the software to a study. Working through the exercises will enhance familiarity with the programs and answer many questions that may arise during a PHABSIM analysis.

Changes Between PHABSIM Version 2 and PHABSIM for Windows

The first obvious change between PHABSIM Version 2 (DOS) and PHABSIM for Windows is use of the Windows graphical user interface and development of the necessary interface programs. The graphical user interface program now includes considerably more code than the analytic al core programs. Additional benefits of developing an extensive interface program include the following: file management is largely done by program; users no longer need to keep track of file names and the risk of removing a file needed at a later step has been essentially eliminated and each study site is kept in a separate, user-specified, project directory, reducing the risk of confusing project files.

In developing this version of PHABSIM, certain decisions were made regarding the structure of PHABSIM data and analyses. All cell definitions now match the data gathering approach taught in the IF305 field techniques course. The cell definition distinctions HABTAE and HABTAV have disappeared and all HABTAV options are now included in HABTAE. Thus, there is no HABTAV program. For consistency, HABTAM cell definitions also match those used in HABTAE. The 100 cell per cross section limit has been eliminated so an unlimited number of cells may be defined for each cross section.

Another difference is the consolidation of AVDEPTH and AVPERM into one program. In doing so, the options and outputs of both programs have been retained.

With these changes have come some differences in computed results. The core analytical programs were translated into C++ from Fortran. Different compilers have different methods of creating machine language so there can be small differences in results of numerical calculations. This is largely due to a combination of order of the calculation, round-off error, method of optimization used within the compiler, etc. While in most situations the differences between the DOS PHABSIM Version 2 and PHABSIM for Windows are very small, there are situations where these differences can accumulate.

The following is an example of possible calculation discrepancies that may occur between the DOS PHABSIM and Windows PHABSIM. Both the Windows and old DOS versions were run for the same study site. The results for a specific cell in the study site at the same discharge and one selected life stage are shown in Table 1.

For illustration, the Weighted Usable Area (WUA) calculation had equal velocity Suitability Index (SI) and channel index SI values (1.0 and 0.91 respectively.) For the species/life stage in question, the depth suitability curve had a steep slope at this point (depth of 0.8 = SI of 0.06 and depth of 0.85 = SI of 0.15). The steep slope of the suitability curve gave a large difference in suitability for a small difference in calculated depth. Thus, noticeable differences in the final computed WUA value between DOS PHABSIM Version 2 and PHABSIM for Windows are likely in situations where the SI criteria are very sensitive to changes in the parameter(s) (depth in this case) for that cell.

Thus, for a relatively small difference of 0.014 in WSL, we show a large difference in WUA for the cell. The WSL model is performing as expected and is within reasonable calibration error for the data set. The differences in water surface elevation have been determined to be due to compiler differences as all calibration parameters were set to the same values in both versions and the internal calculations were traced to ensure they were being accurately performed.

It should be noted that over an entire cross section or over a study site, few cells show these dramatic differences and the resulting calculated WUA differences are usually less than 1 to 2%. Although no study site WUA difference greater than 10% was found during testing, larger differences could occur if a study encounters a situation where numerous cells have differences similar to that illustrated above.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

Table 1. Example of propagating differences between PHABSIM for Windows and DOS PHABSIM.

Conventions Used in This Document

IOC References to Old PHABSIM

PHABSIM Version 2 (DOS) (Milhous et al., 1989) used lines of numerical switches to control program options. These were referred to as IOC (originally input/output control) lines. Users became familiar with selecting program options by remembering items like “IOC 5 set to 2 and IOC 8 set to 1”. While these options are now described in the PHABSIM for Windows interface using text phrases, the old IOC numbers are also displayed with the text to aid experienced users in migrating to PHABSIM for Windows.

Menu Notation

The PHABSIM for Windows software is menu driven through a graphical user interface and the familiar Windows point and click sequence to operate program menus and options. An abbreviated notation convention is used throughout this document to instruct readers in how to make option selections without filling a large amount of space on the page with screen images for each action to be performed.

The following example illustrates how to assign the calibration data sets to each of the desired simulation flows when using the STGQ model. The first item is part of the main menu list that is always displayed at the top of the main PHABSIM window. Subsequent items are submenu items or choices that users will see on the screen as they work across the line. The “/” character is a delimiter to separate higher-level menu items from lower level items. Menu navigation notation is always displayed in **bold** type.

Example notation for using PHABSIM for Windows menus:

“To assign calibration sets to specific simulation discharges, go to **/Models/WSL/STGQ Options/Assign Cal Sets** and click the check boxes for the appropriate discharge/cal set combinations in the table shown”.

To follow this example, the user would click on the main menu item **Models** followed by clicking in order the **WSL** item in a drop down menu, the **STGQ Options** tab, and the **Assign Cal Sets** button to arrive at the data entry table. This notation is further illustrated in Chapter 1.

Table of Contents

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Distributed Parameter Models

Effective Habitat Analysis in PHABSIM

Interpreting PHABSIM and Completing the IFIM Process

Use of the PHABSIM for Windows Menu System

PHABSIM for Windows File Structure

Analysis Limits in PHABSIM for Windows

Summary of Chapter 1

Chapter 2, Hydraulic Modeling in PHABSIM

25

Objectives

Laboratories

Introduction

Terms and Definitions of Open-Channel Flow

Equations Used for the Description of Open-Channel Flow

Continuity and Mass Balance

PHABSIM FOR WINDOWS

vii

Union Analysis

Competition Analysis

Stream Flow Variation Analysis

Manning's Equation Energy Balance and the Bernoulli
Equation Applied Modeling of Water Surface Elevations in
PHABSIM Modeling of the Stage-Discharge Relationship by
Regression Determining the Stage of Zero Flow
Stage-Discharge Analysis using Regression in PHABSIM –
The STGQ

Model Running the STGQ Model A Practical Guide to Modeling Stage-Discharge
Relationships Using the Regression Approache

Modeling the Stage-Discharge Relationship Using Manning's Equation –

The MANSQ Model Running the MANSQ Model MANSQ Options A Practical Guide to
Calibrating MANSQ

Modeling the Stage-Discharge Relationship Using A Step-backwater Approach –

WSP General Theory of the WSP Model A Conceptual Overview of WSP Calibration

Calibration of WSP to Additional Longitudinal Profiles using Roughness Modifiers
(RMODs) Adjusting n Values for Individual Transects Determining Initial Water
Surface Elevations for Calibrated WSP

Models A Step-by-Step WSP Calibration Strategy Hydraulic Controls Divided
Flow Running the WSP Model

Modeling of Velocities in PHABSIM

Calibration and Simulation of Velocities VELSIM with No Measured Velocities VELSIM
with a Single Velocity Data Set VELSIM with Multiple Velocity Data VELSIM
Computational Procedures and Mass Balance Significance of Initial Slopes and
Manning's n Values in VELSIM

Nose Velocities Control of VELSIM Calibration and Simulation Options Evaluating Quality of the Hydraulic
Modeling Evaluation of Water Surface Modeling Predicted versus Observed Water Surface Elevations at
Calibration

Flows Longitudinal Profiles of the Water Surface Elevations Valid Ranges of
Simulated Discharges

Evaluation of Velocity Modeling

Chapter 3, Habitat Suitability Criteria

Objectives

PHABSIM FOR WINDOWS

- Laboratories
- Introduction
- Format
- HSC Categories
- Criteria Verification
- Discussion Items
- Organization of Habitat Suitability Criteria in PHABSIM
 - Accessing Habitat Suitability Criteria in PHABSIM for Windows
- Summary of Chapter 3

Chapter 4, Habitat Modeling

- Objectives
- Laboratories
- Introduction
- Habitat Model Computational Cells
 - Deriving Habitat Computational Cell Areas and Volumes
 - Representative Reaches
 - Habitat Mapping and the Idealized River Reach Approach
 - Integrating Habitat Suitability Criteria Curves and Computational Cell Attributes
 - Basic Assumptions of Habitat Modeling
- Habitat Modeling Options in PHABSIM
 - The Average Parameter Model AVDEPTH/AVPERM
 - Running AVDEPTH/AVPERM
 - The HABTAE Program
 - Setting HABTAE Options
- Description of Habitat Calculation Options
 - ZHAQF Options
 - Using Bends
 - Using Minimum Contiguous Width
 - Use of a Zero Channel Index Value
 - Near Shore Habitats
 - Weighted Usable Area Calculations and Independent Cross Sections
 - The Form of the Habitat
- Calculation
 - Velocity Limits and
- Eddies
 - Minimum Effective Composite Suitability
 - Nose Depth: Empirical Calculation of a Velocity at a Given
- Depth
 - Replacements for Velocity
- Habitat Calculations Conditioned on Adjacent Velocities
 - Selecting the Form of the Adjacent Velocity Calculation
 - Adjacent Velocity Calculation Example
 - Evaluating HABTAE Results
 - Running HABTAE
- Lateral Migration Analysis using the HABTAM Program
 - Setting HABTAM Options
 - Running HABTAM
- Effective Habitat Analysis using the HABEF Program

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Distributed Parameter Models

Effective Habitat Analysis in PHABSIM

Interpreting PHABSIM and Completing the IFIM Process

Use of the PHABSIM for Windows Menu System

PHABSIM for Windows File Structure

Analysis Limits in PHABSIM for Windows

Summary of Chapter 1

Chapter 2, Hydraulic Modeling in PHABSIM

25

Objectives

Laboratories

Introduction

Terms and Definitions of Open-Channel Flow

Equations Used for the Description of Open-Channel Flow

Continuity and Mass Balance

PHABSIM FOR WINDOWS

vii

Union Analysis

Competition Analysis

PHABSIM FOR WINDOWS

Chapter 1. Introduction to the Physical Habitat Simulation System (PHABSIM)

Objectives

This chapter provides a broad overview of the components of the Physical Habitat Simulation System (PHABSIM). The chapter begins with a summary of the Instream Flow Incremental Methodology (IFIM) to ensure readers are exposed to PHABSIM use in the broader context of IFIM. Readers already familiar with PHABSIM can move directly to Chapter 2.

Associated Laboratory Exercise

Laboratory 1 introduces the structure and use of the PHABSIM for Windows software system and Laboratory 2 covers initial data entry steps required for a PHABSIM analysis.

An Overview of IFIM

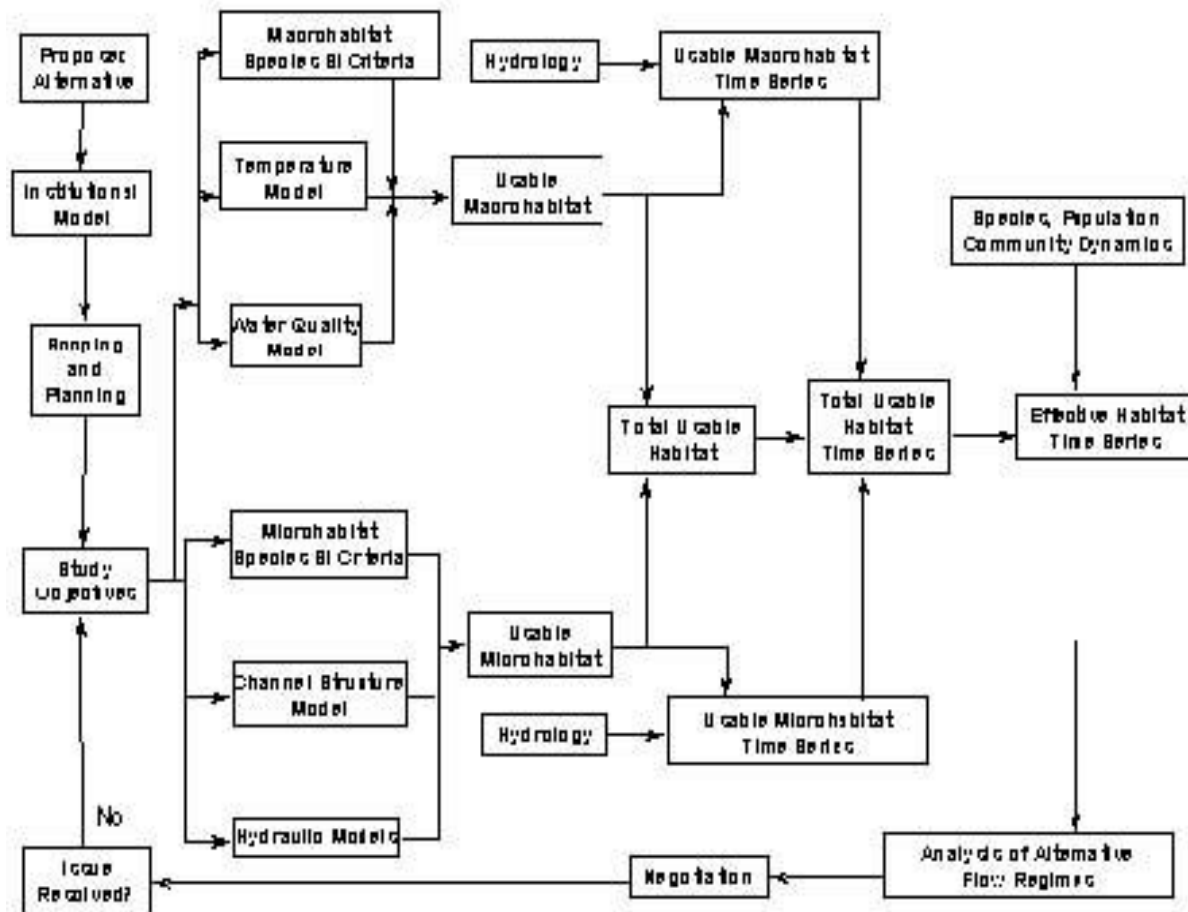
PHABSIM is part of a broad conceptual and analytical framework for addressing stream flow management issues called the Instream Flow Incremental Methodology (IFIM) (Stalnaker et al., 1995) (Figure 1-1). IFIM provides a problem-solving outline for water resource issues in streams and rivers. IFIM and PHABSIM were developed as aids to instream flow decision making. Thus, the structure addresses the decision making environment as well as the techniques for quantifying incremental differences in instream habitat that result from proposed alternative instream flow regimes. Figure 1-1 shows the major components and model linkages of IFIM and where elements of PHABSIM fit into this framework. Integration of PHABSIM with other modeling and analysis efforts is strongly encouraged under the IFIM framework.

“IFIM is based on the analysis of habitat for stream-dwelling organisms under alternative management treatments. One could logically question why habitat was chosen as the decision variable in IFIM when there are so many other factors (such as stream productivity or fishing mortality) that can potentially influence fish populations. The simplest reason for basing the analysis on habitat is that IFIM was designed to quantify environmental impacts, and impacts to habitat are the most direct and quantifiable.” (Stalnaker et al., 1995, p. 16).

The four major ecological components of a stream system that determine productivity for aquatic animals are:

(1) flow regime; (2) physical habitat structure (e.g., channel form and substrate distribution); (3) water quality (including temperature); and (4) energy inputs from the watershed (nutrients and organic matter) (Karr and Dudley, 1981). The complex interaction of these components determines primary production, secondary production, and ultimately the status of fish populations in the stream. In riverine systems, the amount and quality of suitable habitat can be highly variable within and among years. Observed populations and biomass of fish and invertebrates can be expected to be a function of the four components operating on a variety of temporal and spatial scales. Habitat-induced population limitations are related to the amount and quality of habitat available to fish and invertebrate populations at critical stages in their life history. Long-term habitat reductions, such as reduced flows, may be important in determining population and production levels.

Figure 1-1. Major components of IFIM.



IFIM was designed to address these four ecological components in the context of management decisions concerning instream flow. As such, IFIM also includes mechanisms for analyzing the institutional aspects of water resource issues (i.e., the Institutional Model in Figure 1-1), study scoping and planning process, along with techniques for negotiation and resolution.

Two of the most important aspects of any PHABSIM study are that it is set in the IFIM framework and that it is adequately planned. When the problem scoping phase of an IFIM study indicates that the water management issue is an incremental rather than a standard setting issue, PHABSIM can provide the microhabitat component of the analysis (Stalnaker et al., 1995, Chapter 2). The IFIM study may also incorporate models and/or expert knowledge to assess water quality, water temperature, geomorphology, or other characteristic features of the stream and its current and proposed flow regimes that could influence habitat or populations of aquatic organisms within the stream corridor. In any IFIM application, care should be taken to ensure that the factors that control the instream habitat have been fully considered prior to the use of PHABSIM. For example, it would not make sense to only apply PHABSIM to a stream where the sole limit to habitat is water quality. An IFIM study in such a situation may be appropriately limited to only water quality induced limits to habitat quality and quantity. That is,

an IFIM study may be appropriately conducted without use of PHABSIM if physical habitat is determined not to be a major limiting variable. A complete treatment of IFIM is beyond the scope of this document. Users of PHABSIM are strongly encouraged to read “*Stream Habitat Analysis Using the Instream Flow Incremental Methodology*” (Bovee et al. 1998) and “*A Primer for the IFIM*” (Stalnaker et al., 1995) and to conduct PHABSIM analyses within the framework of an IFIM application.

The Purpose of PHABSIM

PHABSIM predicts physical microhabitat changes associated with flow alterations such as a reduction of stream flow from 125 cfs to 100 cfs in June. It provides a variety of simulation tools, which characterize the physical microhabitat structure of a stream and describe the flow-dependent characteristics of physical habitat in light of selected biological responses of target species and life stages. When interpreting PHABSIM results, an assumption is normally made that flow-dependent physical microhabitats are useful in determining carrying capacity and therefore are related to the instream flow needs or impacts of flow variations on fish or other aquatic organisms in streams.

The relationship of physical habitat to fish (or any other aquatic organism) production assumes the production of benefits for fish is limited by the availability of physical habitat. This assumption is not always true. Production may be limited by water quality (i.e., acid rain in the Canadian Shield region), by the activities of man (i.e., land use activities or over-harvesting of some species), or by events and conditions occurring at a temporal and spatial scale beyond the scope of the model application. In essentially all situations, physical habitat is a necessary, but not sufficient, condition for production and survival of aquatic organisms. Thus, PHABSIM results may best be viewed as an indicator of population *potential* in systems where the habitat conditions described in PHABSIM are major population constraints. The IFIM process (see Figure 1-1) contains a critical problem-scoping phase where the analyst(s) must evaluate the plausible limiting environmental variables before embarking on an instream flow needs study. The likely relationship of microhabitat to organism abundance needs to be determined on a case-by-case basis through localized studies or analyst consensus attained within the IFIM process.

To understand PHABSIM one must understand how the general term “habitat” is used. *Macrohabitat* refers to a longitudinal portion of stream within which physical and/or chemical conditions influence the suitability of an entire stream segment for an aquatic organism. *Mesohabitat* is a discrete area of stream defined by the channel geometry with similar physical characteristics, e.g., slope, width, depth, and substrate. Such channel geomorphic units (Hawkins, et. al. 1993) are commonly named pool, run, riffle, etc. *Microhabitat* refers to the small, localized areas within a larger scale mesohabitat unit used by an aquatic organism for specific behaviors (e.g., spawning). Microhabitat is typically described by a combination of hydraulic and/or physical variables such as, depth, velocity, substrate, and cover at a spatial scale of near zero to a few meters. Finally, *total habitat* is an aggregation of available wetted area conditioned by microhabitat and macrohabitat suitability. It is summed for all stream segments, i.e., total habitat is the area of a stream with suitable macro and microhabitat. The microhabitat measures in PHABSIM must be integrated to mesohabitat and total habitat spatial scales and evaluated over the appropriate spatial scale. The PHABSIM software does not directly provide this integration facility. Such integration is easily accomplished using spreadsheets and other commonly available commercial software.

PHABSIM estimates changes in physical microhabitat as a function of flow, but does not directly address other elements of stream systems such as water quality and energy inputs. However, as will be discussed in later sections of this manual, inclusion of other components of interest such as changes in channel configuration can often be accommodated. PHABSIM describes flow-dependent changes in physical components of the system and translates them into an estimate of the quality and quantity of microhabitat for aquatic organisms. Incremental changes in stream flow are used to produce relationships between simulated depth and velocity, measured channel index (e.g., substrate and cover), and microhabitat for target species and life stages. Similar relationships can be produced for broader mesohabitat conditions such as low or high gradient riffles, adequate density of woody debris, pools greater than a specified depth, etc. that can be related to communities as well as individual species of aquatic organisms.

The most commonly used output from PHABSIM is Weighted Usable Area (WUA). This habitat measure is a combination of physical microhabitat quantity and quality. WUA is expressed in units of microhabitat area per unitized distance along a stream (e.g., square feet per 1000 feet of stream or m² per 1,000 m). In IFIM, microhabitat values derived from PHABSIM serve as input to an assessment of alternative stream flow management proposals leading to negotiation of flow regimes. These values may also be used in establishment of mitigation targets and for spatial niche analysis.

PHABSIM is intended for use in those situations where stream flow is one a limiting factor controlling aquatic resources and field conditions are compatible with the underlying theories and assumptions of the various habitat and hydraulic models. In practice, if the assumptions of the various hydraulic and habitat models are reasonably met, PHABSIM can be coupled with habitat time series analysis to incorporate the temporal component of habitat variability (see the IFIM general layout in Figure 1-1) to address a variety of applications which include but are not limited to:

- ☐ Quantification of instream flow requirements
 - Area wide planning
 - Reservation or licensing of water rights
- ☐ Negotiation of water delivery schedules
 - Minimum release schedules
 - Hourly, seasonal and yearly flow regimes (normal and dry year conditions)
- ☐ Impact analysis
 - Stream flow depletion
 - Stream flow augmentation
 - Channel alterations

Note that these outcomes follow from integrating PHABSIM analytical results with alternative discharge time series to arrive at habitat time series. PHABSIM alone does not address the issues of time varying habitat requirements to maintain species life cycles.

The Structure of PHABSIM

The focus of this document is on the PHABSIM software, although some discussions on study scoping, study site selection, habitat mapping mesohabitat classification, cross section placement, and impact assessment are provided for completeness. Figure 1-2 provides a schematic “road map” to the basic modeling elements of PHABSIM. It also presents the flow of information between the various modeling components. The reader is strongly encouraged to refer to “*Stream Habitat Analysis Using the Instream Flow Incremental Methodology*” (Bovee, et al. 1998) for guidance in using PHABSIM as part of an IFIM study.

Figure 1-2 illustrates several key features representing both the conceptual and practical processes for modeling instream habitat in PHABSIM. First, a new project is defined and either an old (DOS) format data file is imported or raw field data is entered using the PHABSIM for Windows data entry interface. Once the data have been entered and checked, the analyst then proceeds with the calibration and simulation of water surface elevations using any (or a combination) of the three available hydraulic simulation models: STGQ, MANSQ, and/or WSP. Upon completion of the water surface elevation modeling, the analyst then proceeds to calibration and simulation of velocities within the VELSIM program. The selection or development and entry of appropriate target species and life stage habitat suitability criteria (HSC) curve data can be done in parallel as indicated in Figure 1-2. Finally, the user will select the appropriate habitat model(s) and set the required or desired modeling options and generate the habitat versus discharge results which are indicated by the box labeled habitat-flow relationship at the lower right of Figure 1-2. At this point, the microhabitat analyses are completed and these results can be integrated with macrohabitat results or utilized directly in the IFIM assessment framework as illustrated in Figure 1-1.

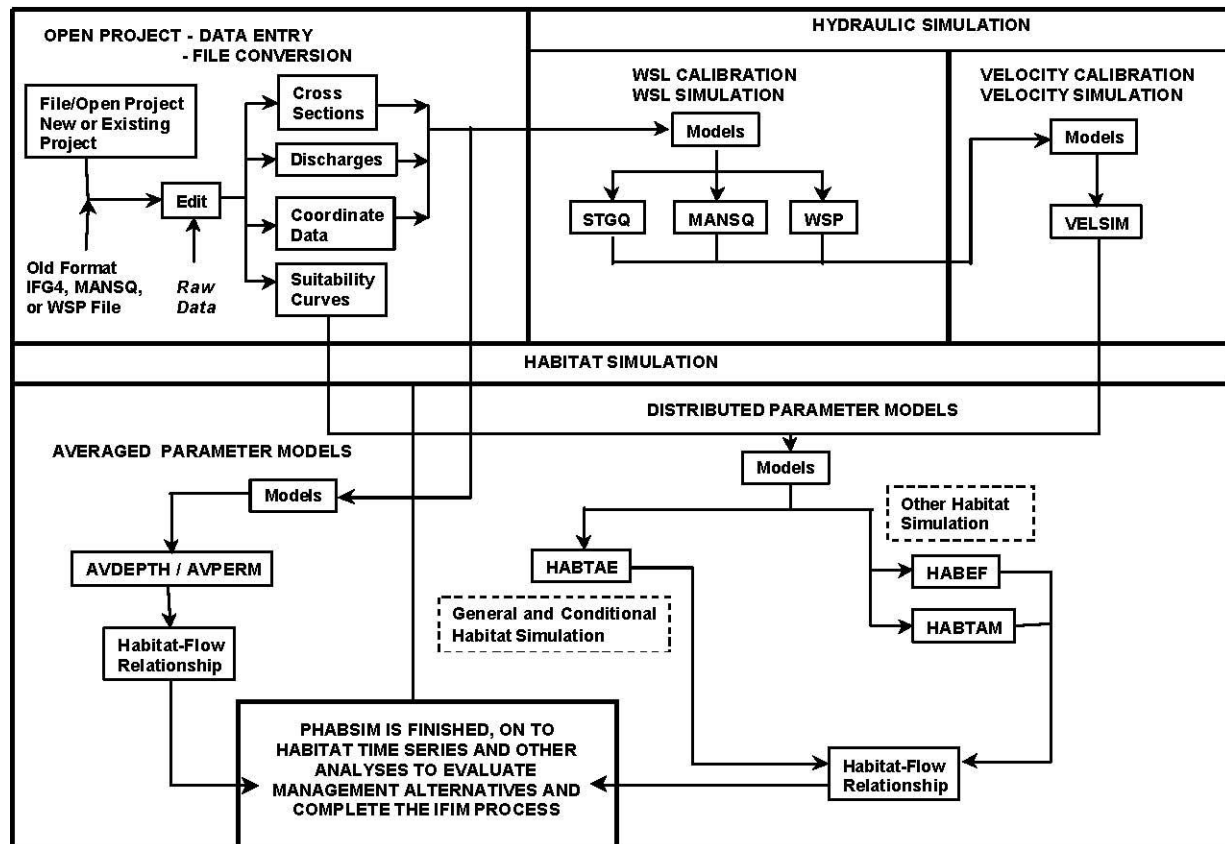


Figure 1-2. PHABSIM for Windows flowchart.

Application of PHABSIM

Once PHABSIM has been determined to be an appropriate analysis tool in the scoping and tool selection stages of IFIM, the general approach to its application can be broken down into nine conceptual steps. These provide an initial outline for the application of the model and a guide to some of the issues involved. Individual studies may deviate from these steps and in all cases users should carefully consider, justify, and document decisions made to structure the analysis for a particular application.

The nine steps (see Bovee, et al., 1998, and Stalnaker et al., 1995) involved in application of PHABSIM within the IFIM context include:

1. Scoping: identification of habitat information needs and study objectives, selection of methods, IFIM Phase II (if PHABSIM is a selected method, proceed to steps 2 – 9 below)
2. Selection of target species or guild, selection or development appropriate micro and or macrohabitat suitability criteria, IFIM Phase II
3. Study area segmentation and study site selection, IFIM Phase III
4. Cross section placement and field data collection, IFIM Phase III
5. Hydraulic modeling, IFIM Phase III
6. Habitat modeling, IFIM Phase III
7. Derivation of total habitat time series, micro and macrohabitat, IFIM Phase III
8. Determination of habitat bottlenecks, IFIM Phase III
9. Evaluation of management alternatives and problem resolution, IFIM Phase IV

Although the remaining chapters of this manual will primarily focus on the technical aspects of the hydraulic and habitat modeling, and to a lesser degree on HSC and assessment frameworks, each of these conceptual steps is briefly described below. Reference materials on study scoping, field data collection techniques, and general approaches on impact assessment frameworks can be found in Bovee, et al. (1998) and *Data Collection Procedures for the Physical Habitat Simulation System* (Bovee, 2000).

Scoping

This section gives a very brief outline of the project scoping process. The reader is encouraged to carefully read Bovee, et al. (1998) prior to engaging in an IFIM or PHABSIM study.

Project scoping should follow a pragmatic approach based on the importance of the issues to be addressed. Project records should include supporting evidence for each of the choices made. Project scoping should address the following questions:

1. **Why?** A statement of study objectives. The outputs, expectations, and requirements of the project should be stated in as much detail as practicable and, where possible, agreed before starting. The “why” is important for determining whether a PHABSIM study is appropriate to the problem.
2. **Where?** Identification of the impacted area or areas to be studied. A decision on the best approach to study site selection must be made, such as whether a critical or representative reach or stratified random sampling based on habitat mapping (mesohabitat classification) is more appropriate (or even a combination of the methods). How should the available mesohabitats be classified? How should mesohabitat study sites be selected? A further consideration is physical access and the location of gauging stations that can provide suitable hydrological data.
3. **Skills?** Identification of skills required and selection of personnel. PHABSIM applications generally require input from a multidisciplinary team, including expertise in aquatic biology, hydrology, hydraulic and habitat modeling, interpretation of PHABSIM outputs, and possibly in negotiation.
4. **Limiting factors?** Use of PHABSIM for a study and interpretation of WUA results will be different if physical habitat is one of the factors limiting target species populations than if it is not limiting. Characterization of macrohabitat issues (e.g., water quality and temperature) and consideration of other factors such as exploitation and stocking, food availability and competition, channel dynamics and sediment transport may be necessary to link

changes in habitat with production of target organisms. Such linkages may be best addressed with other models, or predictive techniques such as multivariate regression analysis or regression quantiles (Cook, et al., 2000). Habitat for food organisms may be modeled using habitat suitability criteria for selected invertebrate species.

5. **Which organisms?** Selection of target species and life stages. It is seldom possible to evaluate the effects of changes in physical habitat on all species or even life stages in a stream. During the scoping process, an indicator species or species which may be the most sensitive to habitat change, which characterizes changes in habitat for an assemblage of other species, or represents a major management interest of the participants in the instream flow assessment may be selected. The management issue driving the study, combined with advice from fisheries and conservation personnel, will determine if the study is to concentrate on a broad range of species, or a small number of specific species or life stages. One method used to select species is to rank them, according to various criteria, including their importance, vulnerability, and extent of available information. Users should locate any existing sources of habitat suitability criteria information; assess their “transferability” (see below); and identify possible strategies for HSC curve development, if existing information is not available or is not sufficiently comprehensive. The importance of characterizing fish species by size/age class cannot be underestimated. Size will have a significant impact on what conditions constitute habitat. The characterization to be used must be compatible with available suitability data.
6. **When?** The temporal aspects of the study must be considered. This includes the timing of field data collection (e.g., when can high/low flows be considered? Is annually variable vegetation growth an issue?). Users are encouraged to construct species periodicity charts (which target species/life stages are important and when?) and determine the availability of suitable hydrological time series data (there is likely to be a requirement for flow data both with and without the artificial influence being investigated).
7. **Who?** The responsible parties must be identified and a clear commitment by those individuals and agencies to carry out the study stated in writing as part of the study plan.

Selection of Target Species and Suitability Curves

Use of PHABSIM involves both the selection of target species as well as the development and/or selection of habitat suitability criteria curves for use in the habitat models. This document does not deal with development of HSC curves. A vital part of a PHABSIM study is defining what conditions provide favorable habitat for the target species being considered. Microhabitat in PHABSIM is defined by water depth, velocity, and channel index. Channel index represents substrate, cover, or other similar immobile variable(s) important in defining the physical habitat requirements of the target species. Habitat suitability criteria (HSC) have been referred to as suitability indices, suitability criteria, preference indices, preference curves, and suitability curves in previous IFIM-related publications and in the general literature. These terms are not entirely synonymous, so the reader is cautioned to check the definitions used in each publication. An example of a set of HSC is provided in Figure 1-3.

It is important that consideration be given to the selection of habitat suitability criteria as early in the scoping process as possible for the following reasons:

1. The scoping process attaches an importance to HSC, which is otherwise easy to overlook. Their simple nature when presented graphically belies the effort behind their development, and interpretation. To simply adopt whatever curves are available after hydraulic modeling is complete may greatly hinder meaningful interpretation of habitat model outputs. Consensus about the HSC among project proponents, regulatory agencies, and other stakeholders early in the project planning process is often essential to successful completion of a PHABSIM study.
2. From the beginning of the analysis the scoping process determines the form and coding of the channel index data to be collected and indicates the areas in the stream that analysts should take care not to overlook.
3. If no acceptable habitat data exist, it may be necessary to initiate a data collection program which can require a long time period, even more so than the site data collection and hydraulic modeling phases of the analysis.
4. PHABSIM results are very sensitive to HSC.

A PHABSIM analysis report should either justify transferring habitat suitability criteria developed elsewhere to the study stream, refer to development of HSC curves specifically for the study in question, or document the agreements by which consensus on HSC curves for the study was attained.

Selection of Target Species

A fundamental step during the initiation of a PHABSIM study is the identification and selection of target species and life stages. Valuable data may be obtained from fisheries collection records, stocking records, and management agencies to determine the historical and existing structure of the fish community. In some stream systems, species and/or life stages (such as migrating salmonids) may only be present in the system for a short period. Historical records of fish numbers can be used in determining whether or not management decisions are to focus only on what is present now or on potential restoration and recovery efforts.

Once the initial list of candidate species and life stages has been assembled, data should be organized into a species and life stage periodicity chart which highlights the seasonal (e.g., at least as small as monthly divisions) use of the study area(s) by different life stages of the target organisms. Next, the availability of existing HSC should be determined and decisions made as to whether to proceed with collection of site specific habitat suitability data, collection of transferability testing data, and/or HSC reviews by species experts, from which a final set of curves can be determined. It may be possible to consider some species or life stages without developing locally derived HSC by using literature values. However, in applied PHABSIM studies, not all the target species or life stages have HSC available even from the broader literature sources. When development of site specific HSC is not an option, users may take a guiding approach to represent components of the fish community by mesohabitat use. Here again, literature values or expert consensus may be needed to define community-based HSC.

Once the initial list of candidate species and life stages has been assembled, data should be organized into a species and life stage periodicity chart which highlights the seasonal (e.g., at least as small as monthly divisions) use of the study area(s) by different life stages of the target organisms. Next, the availability of existing HSC should be determined and decisions made as to whether to proceed with collection of site specific habitat suitability data, collection of transferability testing data, and/or HSC reviews by species experts, from which a final set of curves can be determined. It may be possible to consider some species or life stages without developing locally derived HSC by using literature values. However, in applied PHABSIM studies, not all the target species or life stages have HSC available even from the broader literature sources. When development of site specific HSC is not an option, users may take a guiding approach to represent components of the fish community by mesohabitat use. Here again, literature values or expert consensus may be needed to define community-based HSC. Types of Suitability Curves

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

In general, suitability curves have been classified according to the following categories (Bovee et al., 1998,

Transferability of Suitability Curves

Regardless of how the data are collected, suitability curves will demonstrate some specificity to the stream(s) in which they were developed. With limited resource availability and the high cost associated with development of stream-specific suitability curves, use of HSC from other streams is common. Thus, checking for the appropriateness of the transfer is important. Avoiding development of study-specific HSC leads to considerable cost savings. The investigator must apply professional knowledge and judgment to evaluate if the source curves are meaningful for the current application and transferable. In the IFIM context, it is essential for all parties to agree on the HSC to be used for the study and to agree on their transferability. Thomas and Bovee (1993) and Groshen and Orth (1994) provide methods for quantitatively testing HSC transferability. Manly (1993) provides general guidance on modeling habitat selection by various animals.

For further discussion of habitat suitability criteria curves, see Bovee (1996), Bovee et al. (1998), and Chapter 3.

Segmenting the Study Area and Study Site Selection

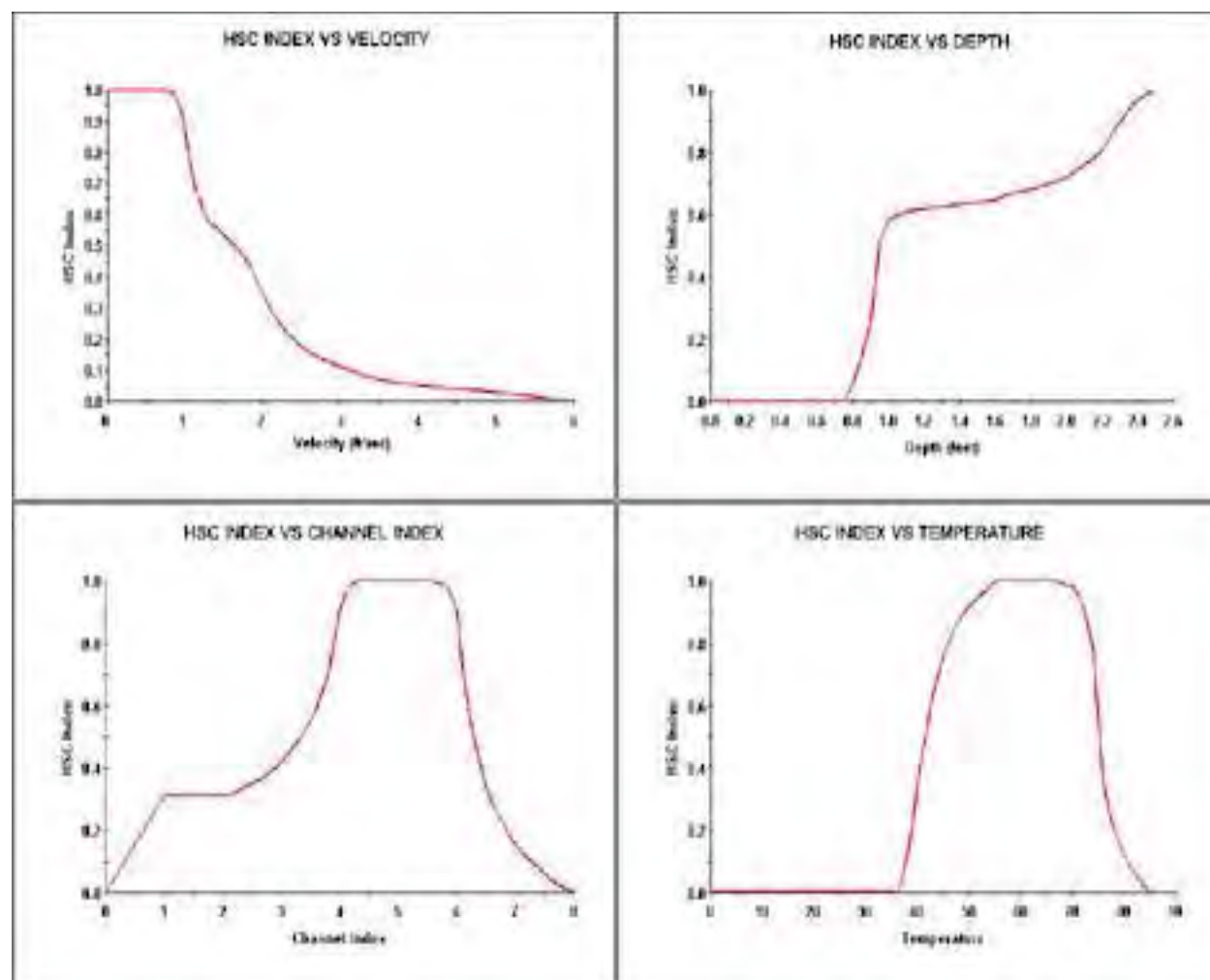
Three approaches are commonly used to sample microhabitat: a critical reach study site, a representative reach study site, or a collection of mesohabitat type study sites. (Bovee et al. 1998) All three require that the stream be segmented using a five-step process. These steps are as follows:

1. Identify the study area boundaries; that is, the reach of stream that is or will be impacted by an altered flow regime.
2. Identify the study area boundaries; that is, the reach of stream that is or will be impacted by an altered flow regime.
3. Segment the study area into hydrologic segments that is reaches of stream that have a homogeneous hydrograph.
4. Segment the hydrologic segments into sub-segments based on geomorphologic factors that influence habitat suitability. For example, within a hydrologic segment there are two reaches that have distinctly different slopes but similar hydrographs. One reach has a mean slope of 1.5 feet per mile while the other is 2.8 feet per mile. Since this factor controls water velocity and sediment (substrate), variables used to describe microhabitat, the hydrologic

segment should be further divided into two sub-segments.

5. Identify the type of study site(s) that will be sampled: critical reach study site, a representative reach study site, or mesohabitat type study sites. Once this decision is made then specific study sites are selected using a stratified random or stratified systematic sampling scheme. If the mesohabitat types approach is used then a mesohabitat type classification must be developed and proportions inventoried within each segment or sub-segment.
6. Place cross sections within each study site using a stratified random or stratified systematic sampling scheme plus place cross sections on all hydraulic controls within or on any hydraulic control having an influence on any portion of the study area.

Figure 1-3. An example of Habitat Suitability Criteria for Adult Brown Trout (one life stage of one species).



The approach used depends on individual study objectives and may involve a combination of the above procedures. The procedure characterizes the study area microhabitat(s) important to the selected target species/life stages affected by the water resource issue in question. When initiating a study, the length of the study area, hydrologic segment(s), and sub-segment(s) over which the assessment is required should be quantified. The more homogeneous the stream segment or sub-segment is in terms of its hydrological and geomorphic characteristics, the more accurate the extrapolation from study site simulations to the entire study area will be.

Critical Reach

This approach uses a specific reach (or reaches) of the stream that is most sensitive to changes in flow, and/or is critical to the success of a particular species' life stage. If, for example, it is believed that the availability of spawning habitat is a limiting factor to recruitment of a particular fish species, then the selection of a study site(s) within the known spawning area may be an appropriate part of a study designed to specify a flow regime optimal for recruitment of the species.

A critical reach may be selected on the basis of basic criteria such as:

1. The reach may be highly affected by, or particularly sensitive to changes in stream flow. For example, the most sensitive reaches with respect to discharge may be elevated portions of the channel, such as riffles and gravel bars. Alternatively, the artificial influence being investigated may only have an impact over a confined area but that area may be highly important with respect to the target species/life stage being considered.
2. The critical reach may act as a biological control limiting a particular life stage of the target species. For example, if the availability of spawning habitat is known to be limiting trout populations, then the only known spawning area within an extensive section of river (e.g., a convex gravel bar) could be an appropriate choice for a critical reach. Or a low flow passage block that limits access to spawning areas could be the critical reach in an investigation.

The assumed role of a particular mesohabitat type as the limiting factor to success of the species/life stage should be verified by sampling whenever possible. For a single species, different mesohabitat types may be limiting to different life stages at different times of the year, and if the study addresses more than one target species, different mesohabitat types may be limiting to populations of the different species. In either case, it is important that the study site(s) represent(s) the full range of mesohabitat types present in the study area. This situation typically involves the use of a representative reach or mesohabitat classification. Some study designs may employ a stratified random sampling approach or a combination of all of the above, which usually involves using a "habitat mapping" strategy for weighting the data in PHABSIM.

Mesohabitat Study Site Selection

One general approach to selecting study sites using a mesohabitat classification is as follows:

1. Within the whole study area in question, hydrologic segments and, if appropriate, sub-segments are identified (e.g., defined by geomorphology or human influences such as channelization, dams, or diversions). This may include portions of a river where the stream hydrology is significantly different such as above or below a tributary inflow or below a water diversion.
2. A classification scheme is developed for delineation of specific mesohabitat types in the stream. These mesohabitat types correspond to channel geomorphic units such as deep glide, shallow glide, pool, riffle, and cascade. This may be accomplished using the skills of people familiar with the stream and the target species in question, as well as those trained in the use of PHABSIM. This may also be approached using any number of different habitat classification schemes published in the open literature or adopted by resource management agencies involved with the study. In addition to identifying different geomorphological features, (e.g., pools and riffles) the distribution of areas having cover (e.g., overhead cover, undercut banks, or floating aquatic plants) and areas thought to be of special ecological importance (e.g., backwater refuges) should be identified where appropriate. The flows under which the mesohabitat classification fieldwork should be carried out must also be considered.
3. The mesohabitat classification itself is then carried out. PHABSIM study sites are established at the selected locations and surveyed according to the techniques described in Bovee (2000). The data are entered into PHABSIM

for Windows using a weighting scheme that causes the resulting habitat simulations to allocate the desired proportions of each habitat type in the final PHABSIM results. (See Chapter 4 for details on this “habitat mapping” procedure.)

Simply stated, the mesohabitat classification procedure involves a classification of mesohabitat types by inventorying (typing and measuring the length of) within each hydrologic segment and sub-segments in the stream. Then specific locations for PHABSIM study sites and cross sections are chosen to characterize these habitats. It may be possible to represent the entire study area with one representative reach. In most circumstances, such as in streams containing complex and variable habitat types, numerous study sites will be necessary. One common approach is to delineate the number and linear distribution of each mesohabitat type within each hydrologic segment and sub-segment using a predefined channel geomorphic unit classification scheme based on actual physical measurements. The investigator can then select cross sections within each of the mesohabitat types within a representative reach(s) within the study area, or a stratified random selection procedure or a combination of methods. The final weights given to each cross section during habitat modeling within PHABSIM are derived from the total mesohabitat classification results. In some studies, only mesohabitat types that are represented by some minimum amount (e.g., at least 5 to 10% of the total area) are included, unless a rarer habitat type is considered critical to the life history needs of the target species. The inclusion or exclusion of mesohabitat types based on the percentage composition or critical nature should be clearly identified during the study scoping process.

Another more detailed approach to mesohabitat classification involves the delineation of study sites of generally similar physical microhabitat identified through a survey which takes spot measurements of habitat variables such as stream width, maximum velocity, depth, substrate, and cover, along with a quantitative discrimination of these habitat variables. Analysis of the distribution of these habitat variables can enable a detailed discrimination of related habitat variables. For example, it may highlight distinctive areas within deep glides or shallow pools. Based on these analyses, specific locations for cross sections can then be accomplished as outlined above.

Still another variation on this basic theme for mesohabitat classification involves the random selection of a starting point within a specific hydrologic segment or sub-segment where mesohabitat classification is conducted over a longitudinal distance equivalent to approximately 20-30 channel widths. Based on the habitat types encountered, each type is assigned as a stratum and the specific habitat unit within a stratum is randomly selected. The location of cross sections in the selected habitat unit is then determined using a random selection process for the location within the specific habitat unit.

No single preferred method exists for selection of study sites or specific cross section locations. The specific approach taken should be determined during project scoping. It is strongly suggested that representatives of all parties in an instream flow issue participate in the cross section selection process.

Cross Section Selection and Field Data Collection

The relationship between cross section placement, number of cross sections, and the subsequent field data collection of the hydraulic properties of the stream are critically important to the successful application and interpretation of PHABSIM.

Cross Section Selection

The number and location of PHABSIM study cross sections is based on the habitat types identified by one of the above mapping strategies. If the distribution of habitats within the stream permits, a series of hydraulically linked cross sections should be chosen to facilitate the collection of field data and increase the flexibility in hydraulic and habitat modeling. The total number of cross sections will depend on habitat diversity, the extent or spatial domain of the study, and resources available. The number of cross sections within each study site will generally be small, but where resources permit, cross sections should be selected to provide replicate samples of habitat types to incorporate the inherent variability within a specific habitat type in a more robust manner.

In addition to the placement of cross sections in target mesohabitat types, it is frequently necessary to place an additional cross section at all hydraulic controls within or influencing each individual mesohabitat type. If a representative reach approach is being used, all hydraulic controls within a study site should be sampled, or if cross sections are clustered into groups, then the hydraulic control at the downstream end of each cluster should be included. Placing of cross sections at the hydraulic controls enables the user to consider the full range of hydraulic models in PHABSIM, including the step-backwater based WSP model. These additional cross sections can be ignored during habitat modeling and therefore will not necessarily contribute to the physical habitat calculations.

A variation on basic mesohabitat classification at a single flow involves mapping the changing proportions of the habitats (as mapped above) at different flows. This information can then be utilized to change the weighting of individual habitat type WUA versus discharge relationships as a function of flows to produce a composite WUA for the range of flows simulated in the study. For example, a stream may contain 30% riffle habitat at low flows, but only 10% at high flows. The particular utility of this type of approach has its own inherent bias. For example, a cross section located in a pool at one discharge may be subsequently classified as a run habitat at an alternative flow.

Field Data Collection

PHABSIM data collection generally requires the following steps to be completed and reported.

1. Units of measurement must be chosen (metric or U.S. customary fps).
2. The selection of target discharges (usually three or more) where field data are required, as well as the selection of the best time to get high, medium, or low flow measurements. Data may be required from more than three flows in order to model the physical habitat correctly. For example, where the bed morphology is complex or where there is seasonal weed growth.
3. Survey headpins are driven into the bank at each cross section. These should be located to provide a stable horizontal and vertical datum and should be securely placed a reasonable distance away from the water to avoid disturbance during high flow events.
4. For each set of linked cross sections, a closed-loop survey through all headpins showing elevations and distances is required.
5. A topographic survey of channel morphology (bed elevation) at each cross section (selected above), relative to the fixed cross section headpin. The investigator should ensure an adequate number of observations to describe the channel cross section and remember that each survey point will be used as a location for hydraulic measurement when covered by water.
6. A record of channel index parameters (substrate, and cover) at each of the points where bed elevation was taken. PHABSIM considers substrate and / or cover to be unchanging throughout the flow range, though the user may evaluate habitat for changing channel index conditions by creating more than one set of study project files.

7. Establish a temporary staff gage to check fluctuations in the water surface elevations during each discharge measurement.
8. Mean column velocities are measured at each survey point across each cross section. A full set of measurements should be taken at several well spaced discharges. This is not essential but it is desirable since it allows the user maximum flexibility in velocity simulation and allows a more comprehensive assessment of simulation errors. Mean column velocity is measured at 0.6 of the depth up to depths of 2.5 ft. In depths greater than 2.0-2.5 feet, an average of readings at 0.2 and 0.8 of the depth is recommended if time and resources allow. See USGS stream gaging guidelines in Rantz and others (1982).
9. At each flow, wading rod depths should be noted at each wetted point where flow measurements are made.
10. At each flow, a survey of water surface levels at each cross section, relative to the cross section headpin. Repeated water surface elevation readings on the left, center and right of the channel provide best accuracy. This provides some data redundancy (wading rod depths are also taken) and provides an essential check on the survey techniques.
11. Any flow changes during fieldwork periods must be noted. A fixed staff gage located at a good cross section for measuring discharge should be read frequently to detect changes in discharge.
12. Field notes describing the stream and in particular every cross section. It is important always to collect as much information as possible.
13. Installation of a data logger for water surface level in lieu of a staff gage at a convenient point (the most downstream cross section or the best cross section for measuring discharge) can provide valuable additional information.

MESC recommends that at least three complete sets of water surface levels and at least a single velocity data set be collected to ensure maximum flexibility in the hydraulic model calibrations. However, in most channels, additional velocity sets at alternative flows are highly advisable, since a single velocity data set is unlikely to reflect the velocity distributions across all flow ranges. Additional water surface and velocity sets are particularly needed in complex channels where it may be necessary to measure several cross sections to capture multiple channels and other features. Available resources may limit time spent on data collection, so it is important to plan in advance on the number of data collection trips and the target discharge ranges necessary to meet data quality

objectives for the hydraulic and habitat modeling for a particular study. For example, in relatively uniform channels, one or two velocity data sets may be adequate. In general, the more data (and more redundant data) one can collect, the greater the anticipated accuracy and reliability of the study. For a more complete description of field data collection considerations and techniques, see Bovee (2000).

Hydraulic Modeling

The techniques used to simulate hydraulic conditions in a stream can have a significant impact on the habitat versus discharge relationship determined in the habitat-modeling portion of PHABSIM. The correct choice of hydraulic models as well as proper calibration often represents the most difficult step in the process of analyzing instream flows.

The hydraulic simulation programs in PHABSIM assume that the shape of the channel does not substantially change with discharge over the range of flows being simulated. In practice, small changes in the bed topography will often occur between field data collection efforts at the high and low flows. If these differences are small, then they are ignored in the analyses. However, if significant changes in bed topography do occur between data collection field trips, these data should be treated as independent estimates of the hydraulic properties within the channel and used as independent data sets (evaluated as different project files) in the hydraulic model calibrations and subsequent habitat simulations.

The simulated hydraulic characteristics of the stream are the water surface elevations (i.e., depth) and velocities, in that order. Water depths are calculated in the habitat programs from water surface elevations simulated in the hydraulic programs. The water surface elevations are assumed to be the same across a single cross section (although depth varies since it is calculated by subtracting the bed elevation from the water surface level). In contrast, velocity varies from cell to cell across any cross section.

The approaches available for calculation of water surface elevations are: (1) stage-discharge relationships, (2) Manning's equation, and (3) the step backwater method. The absolute minimum data set used in the application of PHABSIM requires at least one set of water surface elevations. In standard practice, at least three sets of water surface elevations are targeted for collection along with at least one and preferably additional sets of velocity measurements.

Water Surface Elevation Modeling

The first step in hydraulic modeling within PHABSIM is the calibration and simulation of water surface elevations. Depending on the nature of the field data available, the following programs and approaches can be utilized:

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

all cross sections being analyzed in a given model run be related to each other in terms of survey controls and sequence upstream. That is, each cross section's hydraulic characteristics in terms of bed geometry and water surface elevations are measured from a common datum. The model is initially calibrated to a measured longitudinal profile of water surface elevations by adjusting Manning's roughness, first for the entire study site and then at each cross section. Manning's roughness is then adjusted for subsequent measured longitudinal water surface profiles at other discharges by setting the roughness modifiers used within the model. This approach requires all hydraulic controls within the modeled study site are represented by cross sections.

In addition to these three water surface elevation models, PHABSIM can utilize water surface elevations derived at each cross section from external sources. This approach is discussed in the chapter on hydraulic modeling.

Velocity Modeling

In PHABSIM for Windows, the **VELSIM** program is the principal tool used to simulate the velocity distributions within a cross section over the required range of discharges (i.e., the mean column velocity in each wetted cell in a study cross section at each simulation discharge). The technique relies on an empirical set of velocity observations (i.e., measured velocities) that act as a template to distribute velocities across a channel by solving for the 'n' in Manning's equation (in this context 'n' acts as a roughness distribution factor across the channel). The channel is divided into cells and the velocity calculated for each of these cells. The usual practice is to use one set of velocities as a template for simulating velocities for a particular range of discharges. When more than one set of empirical velocity measurements is available, a commensurate number of flow ranges can be simulated with different velocity templates. The program can be used when no velocity measurements are available. In this situation, velocity will be distributed across the cross section as a function of flow depth.

For further discussion of hydraulic modeling, see Chapter 2.

Habitat Modeling

Habitat modeling transforms information on channel structure, modeled water surface levels and velocities into an index of the quantity and quality of available habitat using the HSC as the transfer function. This index of habitat is referred to as Weighted Usable Area (WUA) and is computed for each cell across each cross section at each modeled flow. The cell values are then summed to produce a composite or study site level WUA for a given discharge, for each separate species or life stage. This enables a relationship to be built up between a range of discharges and aggregate habitat availability for the whole study site. The options used in habitat modeling can affect the predicted habitat area relationship and magnitudes to some extent. Thus, the modeler should select the options in a reasoned manner, and should be consistent when modeling habitat at different sites if the results are to be comparable.

The two general types of habitat modeling options available in PHABSIM are based on either average conditions in an entire stream channel (i.e., the average parameter model) or on the explicit distribution of velocity, depth, and channel index across an entire cross section(s) (i.e., distributed parameter models). Each of these approaches is supported by a set of analysis tools that are described below in general terms and in more detail in Chapter 4. An additional group of effective habitat models deals with the value of distributed habitat under certain changes in flow.

The Average Parameter Model

The average parameter model, **AVDEPTH /AVPERM**, calculates a variety of hydraulic characteristics for each cross section in addition to a study site average view. These include wetted width, wetted perimeter, and wetted surface area, cross sectional area, mean channel velocity, and average depths. They can also be utilized to determine the width of a stream with water that is over some arbitrary depth(s) specified by the user. These programs provide a wealth of information at a cross section or a study site level aggregate and should be examined in most applications.

Distributed Parameter Models

This second habitat modeling category is based on the flow-dependent attributes of depth and velocity at each measured vertical, which are integrated with biological criteria in the form of HSC curves. The primary program using distribution parameters is the **HABTAE** model. In earlier versions of PHABSIM, there were two other habitat models, HABTAT and HABTAV. The functions of these two programs have been combined in the revised **HABTAE** program in PHABSIM for Windows. Options within **HABTAE** allow the user to select habitat calculation assuming the condition within a cell establishes the worth of the habitat in the cell or assuming the condition in a cell plus the velocity in adjacent cells or at another location nearby establishes the worth of the habitat in the cell. The **HABTAE** program also allows habitat to be determined in terms of volume (instead of the surface area), and provides a method for determining the habitat conditions at each cross section.

Effective Habitat Analysis in PHABSIM

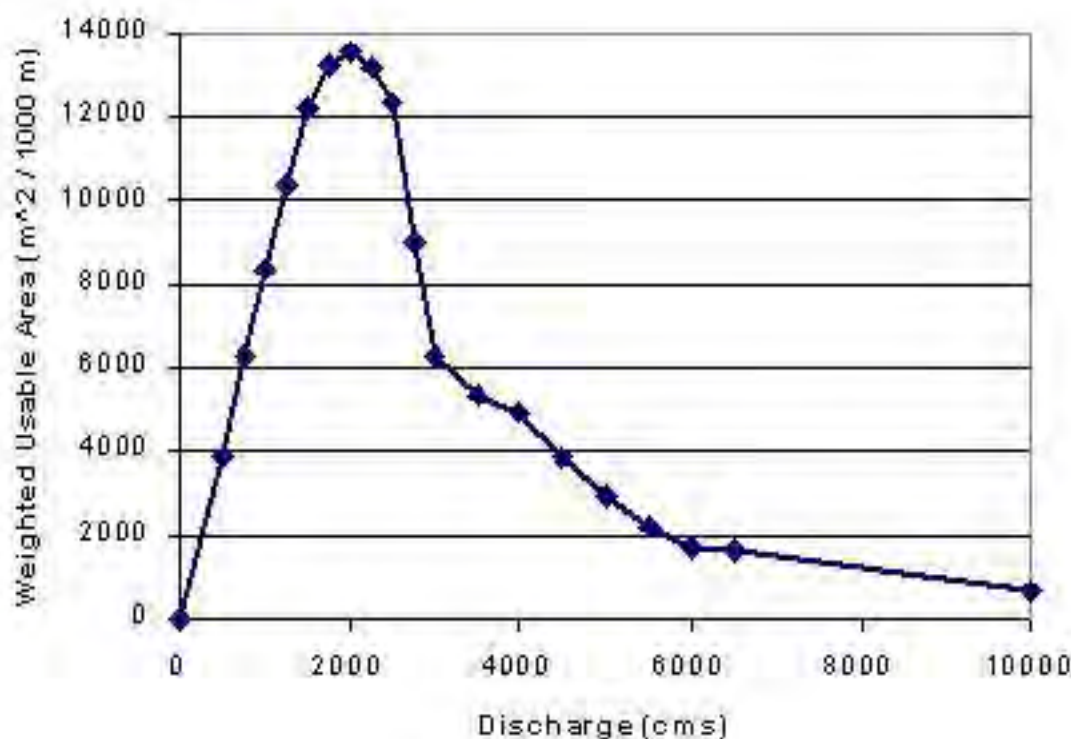
In addition to the two general categories noted above, a third class of habitat modeling involves the determination or evaluation of effective habitat. There are two programs available for effective habitat analysis in PHABSIM. The first is the **HABEF** program, which is used to determine availability of physical habitat considering two flows; in other words, the HABitat that remains Effective when two flows are of importance. This situation often arises, for example, in the evaluation of reducing flows during the spawning period and subsequent incubation period or in hydro-peaking operations that have a daily minimum and maximum flow. In the case of spawning and incubation analyses, the spawning area at a cross section is not „effective’ unless the incubation period flow regime maintains the habitat in a suitable condition for the eggs to hatch.

The second effective habitat model is the **HABTAM** program in which the species can move from cell to cell over a range of starting and ending discharges. In this model, effective habitat is defined as the habitat that remains usable when the species is forced to move due to flow fluctuations. The computational aspects of each of these habitat modeling options are discussed in detail in Chapter 4.

Interpreting PHABSIM and Completing the IFIM Process

The end product of the habitat modeling in PHABSIM is the production of habitat versus discharge functions for each target species and life stage (Figure 1-4). These relationships represent the starting point for assessment of alternative flow regimes or impacts of a proposed project. In many instances additional analyses of such factors as channel and riparian maintenance flows, and/or water quality and temperature modeling will be needed to assess alternate flow regimes.

IFIM provides an assessment framework for use in the interpretation of PHABSIM results. In IFIM, stakeholders are encouraged to reach consensus on evaluation of these results in the context of the water resource decision at hand. Fortunately, there are a number of analytical approaches that can aid the investigator and water resource manager in this decision process. From a physical habitat modeling perspective, the most common (and recommended) approach is to conduct time series analysis based on the existing or anticipated flow regime(s) for the project. Habitat time series illustrate the dynamics of the temporal habitat change for a particular species and life stage during each season or critical time period under historical, existing, and proposed project flow scenarios. This aspect is one of the critical distinctions between an application of PHABSIM (which produces a habitat-flow relation) and a true IFIM study (which produces numerous alternative habitat time series). Some examples of



using PHABSIM within an IFIM study are treated in Chapter 5.

Figure 1-4. Example of a habitat-discharge relationship for a single life stage.

Habitat time series analysis quantifies project impacts or benefits in terms of habitat gains or losses when comparing flow scenarios to the selected project base line conditions. These analyses can also be used to generate habitat duration curves on a seasonal basis or compute habitat conditions that are continually below some prescribed threshold. It is a matter of professional judgement as to what adverse impact or benefit is represented by any quantitative change in habitat area or as a percentage change from baseline scenarios. Often the kind of water resource issue and the importance of the target species to the resource manager, dictate the level of impacts or benefits that are considered acceptable. In addition, establishing an instream flow regime will often require the integration of water quality or temperature during critical periods. It is also common to use alternative techniques such as channel maintenance flow computations during the peak runoff periods to select an appropriate flow regime rather than rely solely on the PHABSIM model outputs.

There are several approaches to habitat modeling available in PHABSIM. See Chapter 4 for treatment of each of the habitat models and their numerous options for generating and aggregating habitat values.

This concludes the overview of the background and general concepts in PHABSIM. This chapter concludes with an introduction to the PHABSIM for Windows software.

Using the PHABSIM for Windows Menu System

The general steps for using the interface consist of clicking on the appropriate menu, tab, or button items to enter data, select options, run programs, or view output. In this manual each of those steps is presented in text in the following format:

Main Menu/Next Menu/Next Menu or Tab: Instructions for what you should do.

For example to run the STGQ model and generate simulated water surface elevations, click on **Models**, then **WSL**, followed by **Method** and the **STGQ** radio button. Then either click the cells in the data entry table where you wish to enter stage or click the **Set All** button to the right. That sequence of operations is noted in the documentation as:

/Models/WSL/Method/STGQ: Select **Set All** or click the cells for the cross section and discharge for which you wish to run the STGQ model.

The actions are:

Move mouse to **Models** item in the main menu, click. Move mouse to **WSL** drop down menu item, click. Move mouse to **Method** tab (if not already showing), click. Move mouse to radio button (round button) for the model you wish to use (in this case **STGQ**), click. A black dot should appear in the middle of the round button. Move mouse to the individual cells for cross section and discharge where you wish to use STGQ and click each cell or click the **Set All** button.

The notation **../Method/WSP** is used in some places to abbreviate long entries such as **Models/WSL/ Method/STGQ** when moving within the same set of tabs.

The following figures illustrate these operations.

Figure 1-5. Selecting the Models Menu Item. Move the cursor over the word Models and click. A drop down menu with the model categories will appear.

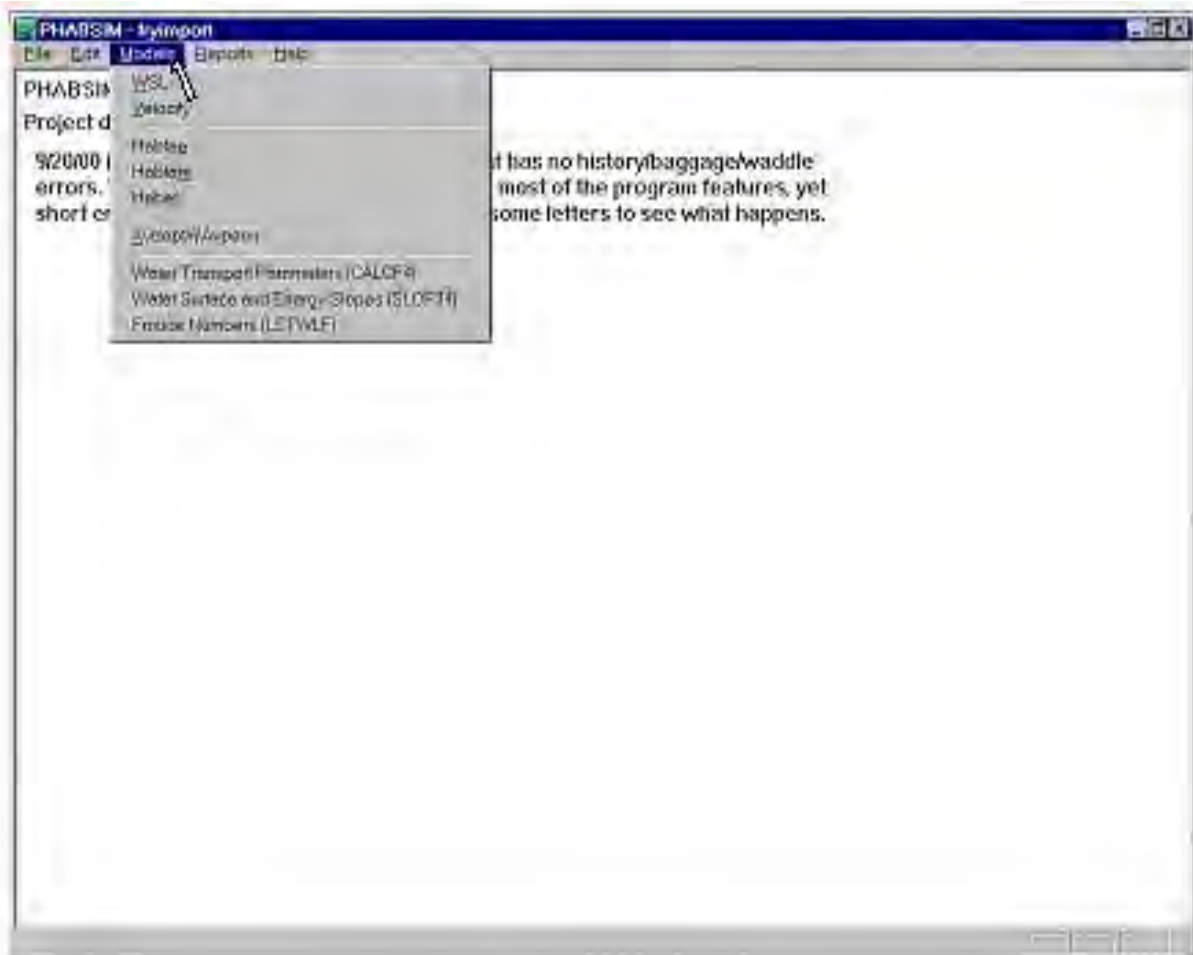


Figure 1-6. Selecting the WSL Menu Item. Move the cursor over the WSL item on the drop down menu and click.

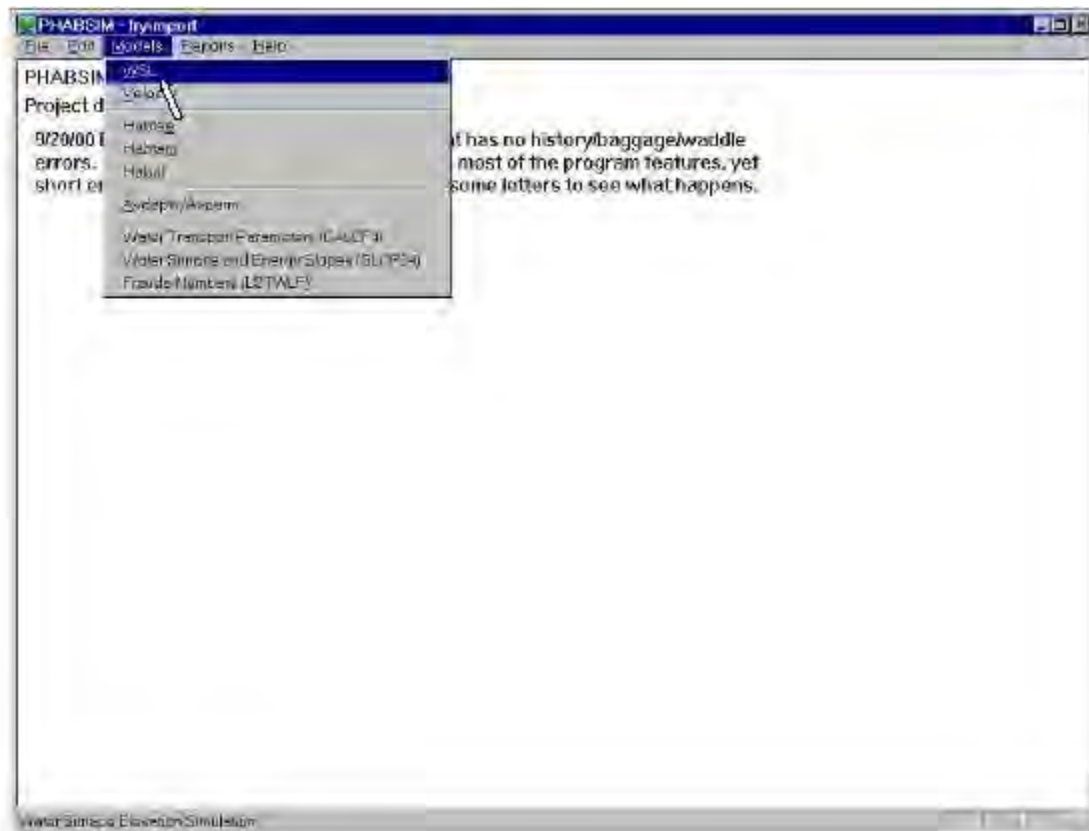


Figure 1-6. Selecting the WSL Menu Item. Move the cursor over the WSL item on the drop down menu and click

Figure 1-7. Selecting the STGQ Radio Button followed by Set All, Result of the Set All Operation is shown.

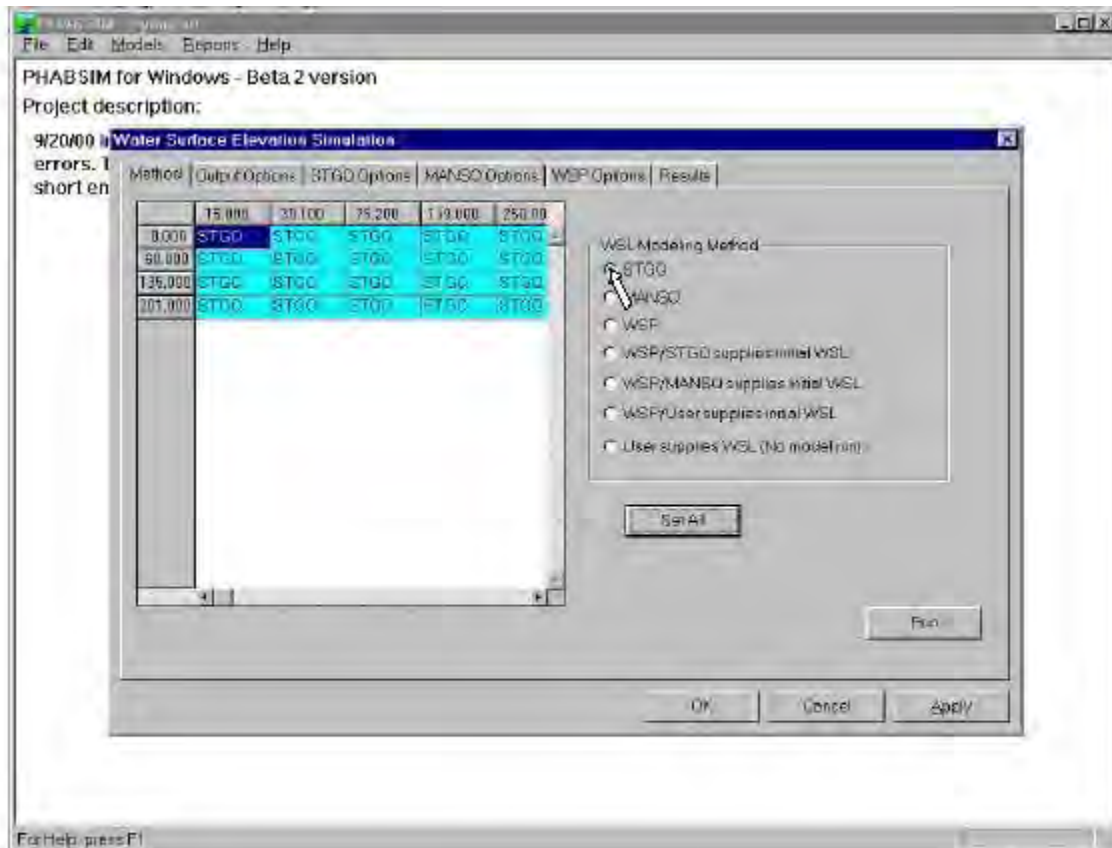


Figure 1-7. Selecting the STGD Radio Button followed by Set All, Result of the Set All Operation is shown.

This notation is used throughout this manual in lieu of repeating this sequence of figures for each operation to be performed. If the operations are not clear, click the first two or three items in the sequence and read the screen that appears. The next item in the command list will be shown on that screen.

PHABSIM for Windows File Structure

PHABSIM for Windows uses a file structure designed to allow maximum flexibility in the analysis and reduce the amount of file management demanded of the user. To accomplish this, each study site is defined as a “project”. When creating a new project, the software will create a folder with the project name. Within the folder there will be several files with the project name and an extension. Most of the files are in a binary format and cannot be read without running PHABSIM for Windows. Table 1-1 contains a general description of the project files.

Table 1-1. Project files.

<project>.phb - general project information binary <project>.pxs - cross section data binary <project>.ppt - point data
-binary <project>.pxp - cross section point index -binary <project>.pcl - calibration set data -binary <project>.pcv -
suitability curve data -binary <project>.opt - project options -binary <project>.history - project history file -text
<project>.hyd - hydraulics output -binary <project>.zout# - accumulating ZOUT files -text <project>.zvaff - velocity
adjustment factors -binary <project>.zhaqf - ZHAQF habitat-flow relation output -binary <project>.11111e - HABTAE
output for curve 11111 -binary <project>.11111m - HABTAM output for curve 11111 -binary <project>_options.txt -
dump of the options -text. <filename> - communication files have no extension binary <filename>.bin - binary internal
communication files binary

Notes:

- The history file grows as analysis progresses. It is a text file that may be viewed with a text editor to see what steps have been taken in the analysis. This is especially useful when preparing testimony or when preparing reports where the analytical choices must be explained.
- A separate ZOUT file is created for each program run in the PHABSIM suite. ZOUT files contain analysis results and error messages. *The user is recommended to search the latest ZOUT file with a text editor after each model run for error messages.* The number of ZOUT files will grow as the analysis progresses. One may delete ZOUT files as results are stored in the project database. However, if files are deleted, the numbering sequence will start over with 1 or the next number above the lowest existing ZOUT. If you delete ZOUT10 through 17, ZOUT10 will be the next one created.
- A separate numbered result file is created for each species/life stage in a habitat simulation. The number is the habitat suitability criteria curve number for the particular species/life stage. These are binary files that contain the habitat-flow relation resulting from running HABTAE or HABTAM. The files are used at later stages of the analysis process and are the source of display of habitat results.
- The project_options.txt file is created when the user instructs the interface to record options in **/Reports/Record Options**.
- The project.hyd file contains cell-by-cell depth and velocity information.
- The project.ZHAQF file may be produced by HABTAE or HABTAM.
- Cell-by-cell habitat results will be produced for each selected species/life stage. Those results will be contained in files named project.xxxxxxe, where the x's represent the HSC number. The extension will have an "e" or "m" matching the HABTAE or HABTAM program that produced the file.
- The internal communication files should be retained with the project as they can be useful when asking for assistance if the program fails.

Analysis Limits in PHABSIM for Windows

PHABSIM for Windows contains few limits on the number of items that may be analyzed in one project. There is no limit on the number of cross sections that may be included in a project, although there is a practical limit of about 50 cross sections due to the difficulty of tracking all of the habitat issues that may be addressed. A second practical limit applies when using the step-backwater hydraulic model; numerous pool riffle sequences may prove difficult to calibrate unless cross section placement fully satisfies all of the assumptions of the model. Finally, smaller projects generally run faster and are easier to manage.

The number of cells on a cross section is not limited. This is in contrast to PHABSIM Version 2 for DOS, which had a 100 point limit per cross section. Also, the number of digits in x, y, and z position values is not limited by hollerith field lengths as in the previous version.

A limit of 30 discharges per habitat simulation has been retained in PHABSIM for Windows. Both programming costs and run time considerations contributed to this decision. In the event you need to simulate more than 30 discharges, we suggest you make a copy of the project and split the discharge range between two otherwise identical projects.

Summary of Chapter 1

This chapter introduced PHABSIM as a component of the Instream Flow Incremental Methodology. A general outline of its use within the IFIM framework was given. Several activities such as study site selection, field data collection, and habitat suitability curve development were briefly described. Those activities are outside the scope of the PHABSIM software and are not further elaborated in this manual. The remaining chapters deal with the structure and use of the PHABSIM for Windows software. They are presented in the order of a typical PHABSIM analysis beginning with hydraulic analysis in Chapter 2.

Chapter 2. Hydraulic Modeling in PHABSIM

Objectives

This chapter introduces the basic concepts of hydraulic simulation in PHABSIM followed by a detailed explanation of the specific calibration and simulation options for each hydraulic model within PHABSIM. Calibration and simulation of water surface elevations are treated first followed by calibration and simulation of velocities. Specific steps in use of the software for each stage of hydraulic simulation are presented. The chapter concludes with a general discussion of how to evaluate hydraulic modeling results.

Laboratories

The associated laboratories for this material are contained in Laboratory Exercises 3-7. They introduce the three principal water surface modeling options within PHABSIM, as well as the general approaches to velocity simulations. Laboratory 3 introduces the stage-discharge modeling of water surface elevations using STGQ, Laboratory 4 covers the use of the MANSQ model for this purpose, while Laboratory 5 introduces the use of the step-backwater model (WSP). Finally, Laboratory 6 covers the use of the VELSIM model for velocity simulations.

Introduction

Flow in an open channel is a three-dimensional process. It includes response to change in the channel shape, secondary currents, and it varies continuously across and along the axis of the stream. Models of varying complexity capture the overall streamflow process to different degrees. In PHABSIM, the Water Surface Profile model (WSP) uses the step-backwater method to obtain a one-dimensional representation of flow. The STGQ and MANSQ models use empirical means to obtain similar transect-based representations of flow. The hydraulic models in PHABSIM operate with assumptions of a fixed bed profile and a sloped water surface that is level across each cross section. There are many empirical relations used to simplify flow representations so they can be represented on transects, rather than continuously. Thus, flow representations within PHABSIM are discretized as cells located across transects. The influence of the assumptions and one-dimensional form of PHABSIM models will become more apparent as the reader progresses through this chapter.

Hydraulic modeling within PHABSIM characterizes the physical attributes within the stream (i.e., depth, velocity, and channel index) over a desired range of discharges. This characterization could be accomplished by direct empirical measurements taken at small increments of discharge covering the range of discharges of interest for a habitat study. However, time, safety and funding constraints typically prevent this empirical approach. Fortunately, it is possible to sample the stream's hydraulic properties at a few target discharges and then rely on these data to calibrate one or more hydraulic model(s) and use the model(s) to predict the stream hydraulic attributes over the full range of discharges of interest in the study. The success or failure of this effort is dependent on the quantity and quality of the field data, the complexity of the physical nature of the stream, and ultimately the ability of the hydraulic models to reflect the physical processes in the stream.

The material in this chapter represents concepts and application strategies of elements contained in the hydraulic simulation portion of the information flow within the PHABSIM system as indicated by the area labeled hydraulic simulation in Figure 1-2. The chapter concludes with a section on evaluating hydraulic model results.

Terms and Definitions for Open-channel Flow

Prior to presentation of these specific modeling approaches within PHABSIM, a brief introduction to the vocabulary and physical setting of open channel flows is necessary. A more technical and detailed treatment of the hydraulics of open channel flow can be found in any number of general texts on hydraulics such as Henderson (1966). Those readers who are interested in a more rigorous treatment of hydraulics should consult that or similar works.

The following terms and their definitions are important since they constitute the vocabulary of hydraulic analysis terminology within PHABSIM related to the analysis of open-channel flow and in particular to the use of hydraulic modeling options for the specific models within PHABSIM. The relationships between these terms and physical properties within a river channel or cross section(s) are illustrated in accompanying figures where possible. Figure 2-1 provides an idealized representation of a stream reach showing the location of several cross sections (transects), a hydraulic control, and a lateral view of a typical cross section profile.

Cross Section: A two-dimensional (width and depth) section derived from measurement of lateral distance and stream bed elevation across a stream channel that is perpendicular to direction of the flow and is synonymous to a transect. These are indicated in plan view by T_1 , T_2 , etc, in Figure 2-1 and in lateral view for T_3 .

Reach Length: Reach length is the distance that the current cross section is located from the previous cross section and, therefore, by convention is measured in an upstream direction. The downstream-most cross section has a reach length of zero and as illustrated in Figure 2-1, the reach length for T_2 is 35 feet, while the reach length for T_3 is 42 feet. In practice, both the left bank and right bank distances between adjacent transect head pins are measured and typically the average distance is used as the reach length for hydraulic modeling. In hydraulic modeling within PHABSIM, the actual reach length is only important when using the WSP hydraulic model since WSP uses this distance to dissipate the energy between adjacent cross sections. Since the STGQ and MANSQ models analyze each cross section independently, reach lengths play no role in these hydraulic models. The use of reach lengths and reach length weighting factors (upstream weighting factors) is critical in habitat modeling since these factors are used to derive the longitudinal dimension of the habitat cells and thus contribute to determining habitat area. Reach lengths are discussed in more detail in the section on habitat modeling.

Backwater: An area of stream where the water surface elevation is controlled by a hydraulic control. An example of a typical backwater area is a pool upstream of a riffle. Backwaters also occur in secondary (or side) channels where water “backs up” from the main channel, though flow through the side channel is cut off at some point upstream.

Hydraulic Control: A section of the channel which “controls” the water surface elevation of the stream in an upstream direction under sub-critical flow conditions or in a downstream direction under super critical conditions. Hydraulic controls are most often associated with a shallow and raised section of stream or a steep section of the stream such as a riffle as illustrated in Figure 2-1. Hydraulic controls typically have a higher bed elevation than the backwater areas upstream. Hydraulic controls can also occur at major channel constrictions.

Backwater: An area of stream where the water surface elevation is controlled by a hydraulic control. An example of a typical backwater area is a pool upstream of a riffle. Backwaters also occur in secondary (or side) channels where water “backs up” from the main channel, though flow through the side channel is cut off at some point upstream.

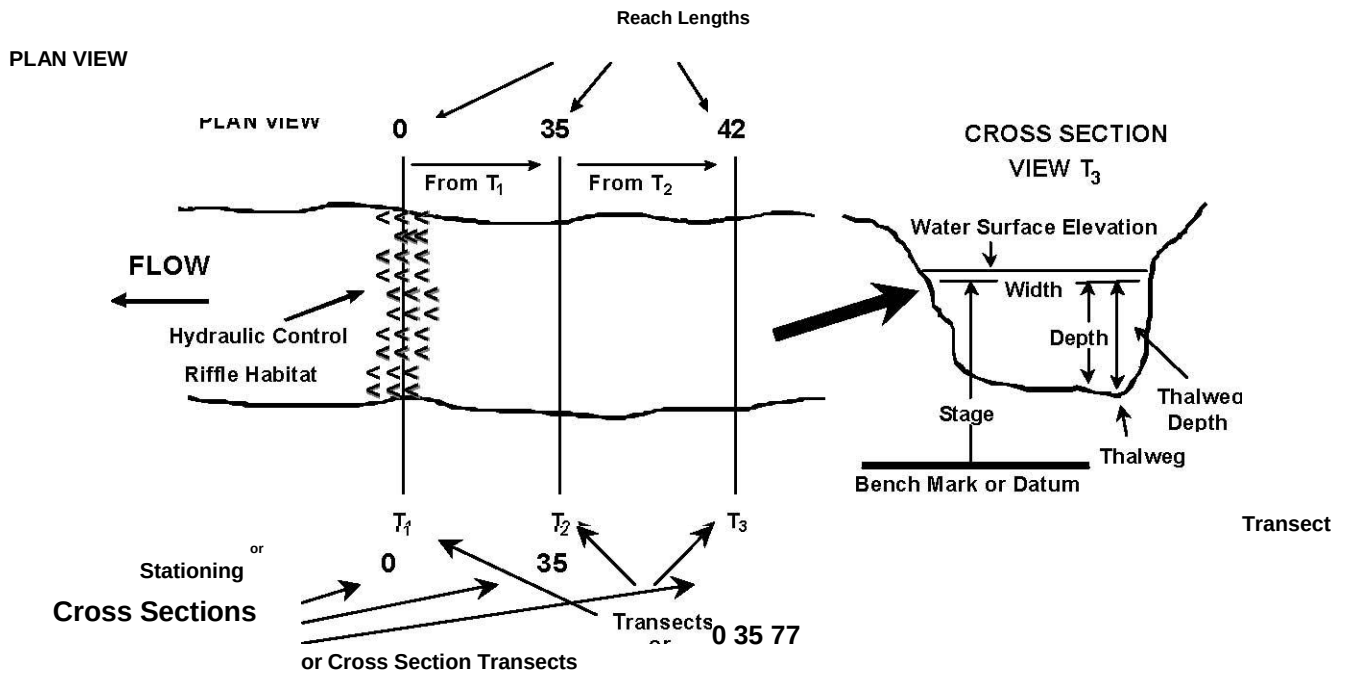


Figure 2-1. Schematic of a PHABSIM representative reach and a typical transect.

Hydraulic Control: A section of the channel which “controls” the water surface elevation of the stream in an upstream direction under sub-critical flow conditions or in a downstream direction under super critical conditions. Hydraulic controls are most often associated with a shallow and raised section of stream or a steep section of the stream such as a riffle as illustrated in Figure 2-1. Hydraulic controls typically have a higher bed elevation than the backwater areas upstream. Hydraulic controls can also occur at major channel constrictions.

Water Surface Elevation (WSL): The height of the water surface at a cross section as measured (or predicted). The WSL can also be determined from the streambed elevation plus water depth. The WSL is also called the water surface level.

Stage: The elevation, or vertical distance of the water surface above some datum (i.e., height relative to the established bench mark used during surveying of the stream geometries or as predicted from the hydraulic models in PHABSIM. Stage is equivalent to WSL.

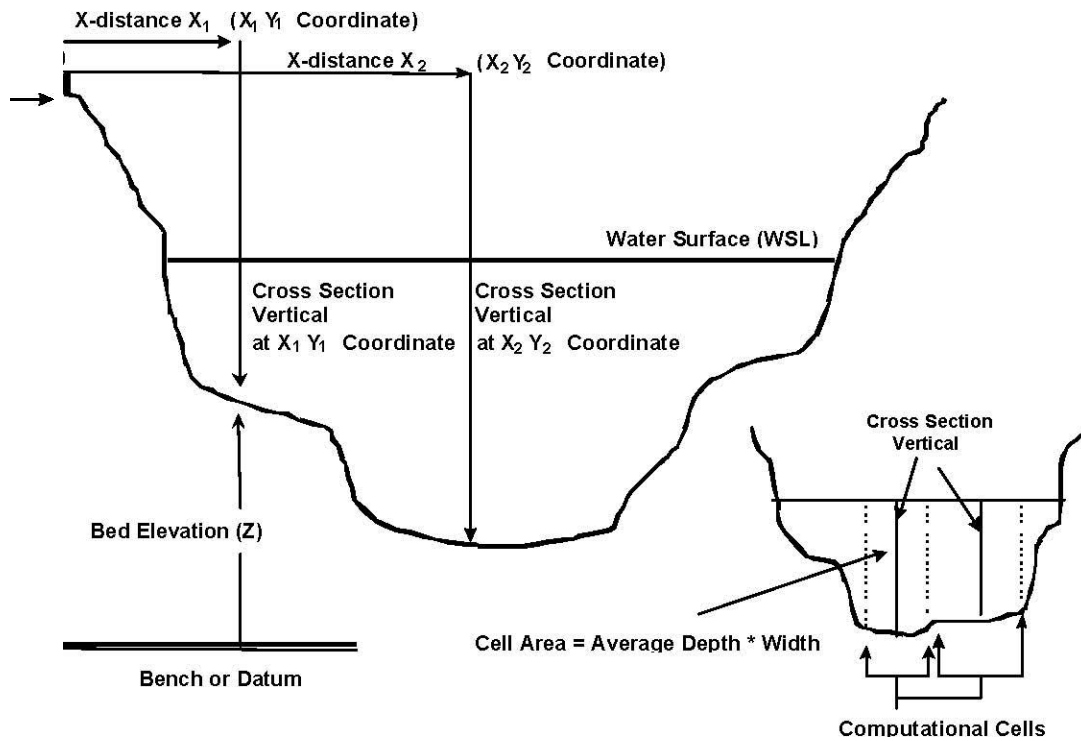
Depth: The vertical distance from a point on the streambed to the water surface. Depth is either measured or computed for each vertical.

Hydraulic Depth: Equivalent to the mean depth at a cross section; hydraulic depth is derived by dividing the cross sectional area of the flow by the width of the water surface.

Thalweg Depth: The vertical distance from the lowest point of a channel section (the thalweg) to the water surface. It is equivalent to the maximum depth of a cross section.

Width: The distance across a channel at the water surface, measured normal (i.e., perpendicular) to the flow.

Figure 2-2 provides a representation of a cross section view of a cross section (or transect) which relates the following hydraulic field data measurements to their equivalent terms as used by the various hydraulic (and



habitat) models.

0

X-distance X2 ($X_2 Y_2$ Coordinate)

Head Pin

$$\text{Cell Area} = \text{Average Depth} * \text{Width}$$

Bench or Datum

Figure 2-2. Schematic view of a Cross Section showing hydraulic measurement and modeling terms.

X-distance (X): Lateral distance measured from either the left or right bank head pin across the stream perpendicular to the axis of stream flow. X-distance must always increase when moving across the transect for use in the PHABSIM hydraulic models. The X-distance (X) in combination with the bed elevation (Y) represents the coordinate points or verticals that define the cross section geometry in PHABSIM.

Bed Elevation (Z): Height of the stream bed measured from some established bench mark or elevation reference point for the transect or cross section. Bed elevations are measured at each X-distance along the cross section. The bed elevation (Z), in combination with the X-distance (X) represents the coordinate points or verticals that define the cross section geometry in PHABSIM.

X,Y,Z-coordinate: The X-distance as measured from a head pin to a particular vertical along a cross section. The Y distance is the accumulated distance upstream from the first transect in a study site. Identifying transects by their Y distance is also called “stationing” (see Figure 2-1). The Z-distance is the elevation of the stream bed at the X,Y-coordinate above the datum.

Cross Section Vertical: An imaginary line perpendicular to the water surface at each X-distance where the bed elevation, depth, velocity, and channel index (see chapters 3, 4 and glossary) values are recorded and used to represent the hydraulic properties for the cross section.

Computational Cell (hydraulic programs): The area of the cross section defined by one-half the distance to each adjacent cross section vertical such that the cross section vertical resides at the approximate center of the “cell”. Computational cells are used by the hydraulic simulation programs for computing the water’s edge based on the simulated water surface elevation, the predictions of velocities and individual cell discharges.

Habitat Cell (habitat programs): The area of the cross section lying between adjacent cross section verticals. Habitat cells have the average of the depth predicted at the bounding verticals and the average of the velocity at those verticals. The length of a habitat cell is determined from reach length and transect weighting factors.

Cell Discharge (q): Discharge computed within each computational cell based on the cell area and mean column velocity.

Cell Area (a): Computational cell area derived from the average difference between bed elevation and water surface elevations at the cell boundaries and the width of the computational cell.

Figure 2-3 shows an idealized representation of a cross section which defines the relationship between the following terms and definitions.

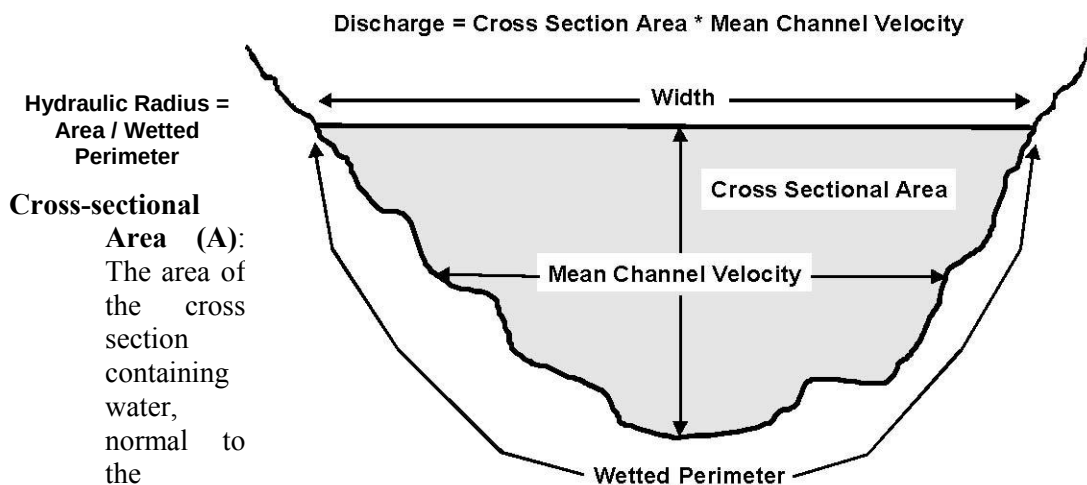


Figure 2-3. Cross section hydraulic terminology.

Wetted Perimeter (P): The distance along the bottom and sides of a channel cross section in contact with water at a specific discharge and is roughly equal to the stream width plus 2 times the mean depth (hydraulic depth).

Hydraulic Radius (R): The ratio of the cross sectional area to wetted perimeter, $R = A/P$. For wide shallow channels, R approximates the hydraulic depth. Also called characteristic length (L).

Mean Channel Velocity (V): The mean rate of water movement or travel past a given location. It should not be confused with discharge. Mean channel velocity at a cross section can be computed by dividing the discharge by the cross sectional area.

Mean Column Velocity (v_i): At a vertical i, mean column velocity is usually measured at 60% of water depth (measured down from the water surface) if the depth is less than 2.5 feet. When depths exceed 2.5 feet, measurements are made at 20% and 80% of the water depth and the two values are averaged to obtain the mean column velocity.

Discharge (Q): The rate of flow, or volume of water flowing past a given place (i.e., a cross section) within a given period of time, traditionally expressed as cubic feet per second (cfs).

Figure 2-4 illustrates the relationship between important hydraulic parameters and definitions applied between adjacent cross sections. These items define the principal factors and terms used by the WSP model to compute

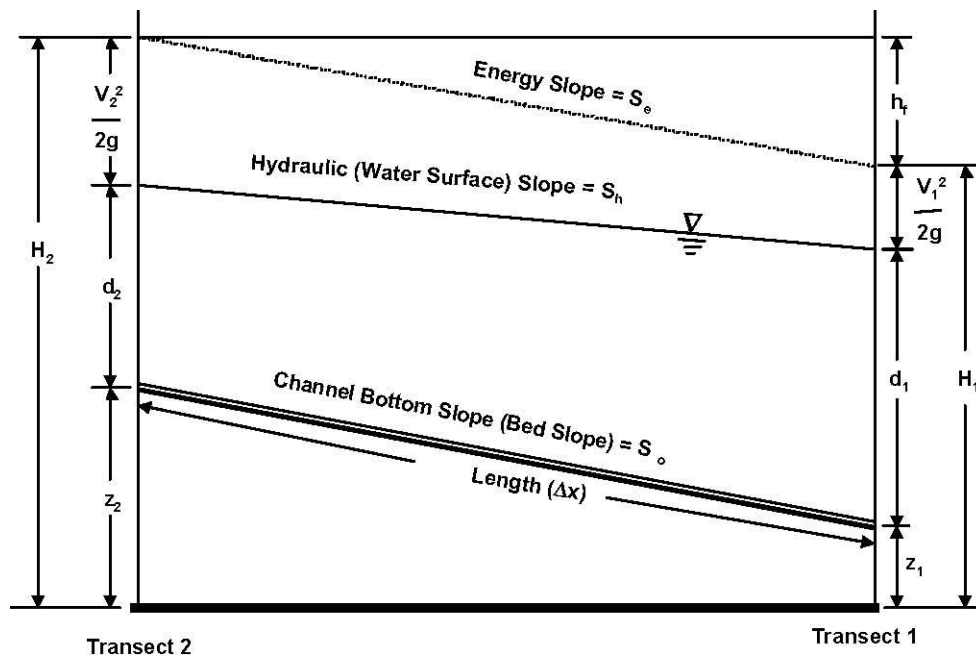


Figure 2-4. Energy relationships between transects.

Transect

1Transect 2

water surface elevations.

Upstream Transect Downstream Transect

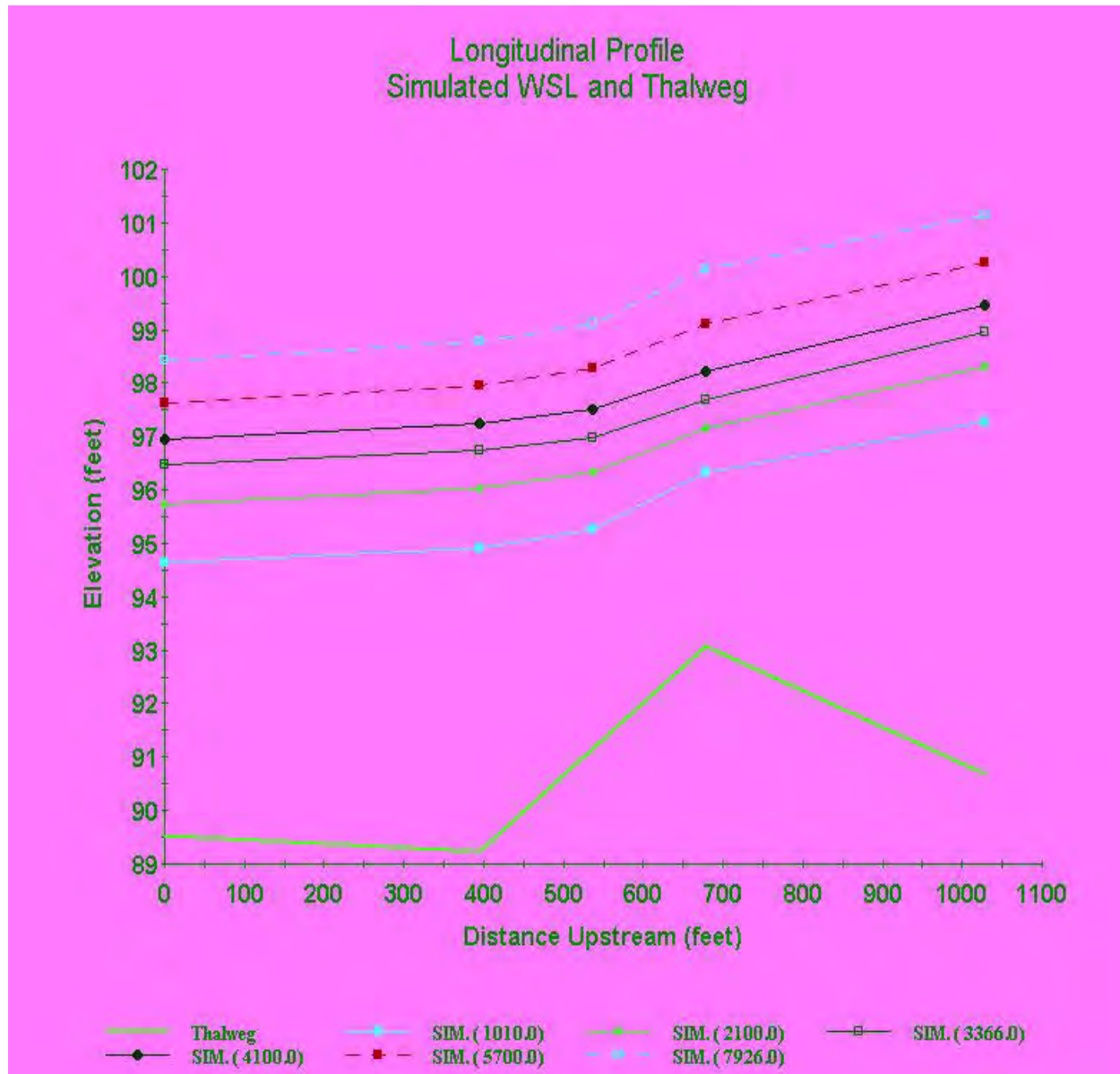
Hydraulic Slope (S_h): The change in elevation of water surface between two cross sections, divided by the distance (reach length) between cross sections.

Bottom Slope (S_o): The change in average elevations of the bed between two cross sections, divided by the length.

Energy Slope (S_e): Change in total energy (potential and kinetic) available, divided by the length.

Velocity Head: The square of the velocity divided by 2 times the acceleration due to gravity. Velocity head is computed at adjacent cross sections in order to estimate the energy slope between the adjacent cross sections. This is the kinetic energy term in the energy balance equation.

Longitudinal Profile : A plot of the water surface elevations at each cross section within a reach versus the cumulative reach length distances for the cross sections. It typically includes the thalweg elevations. Longitudinal profiles can be represented by either calibration data, simulated values, or both. These plots are used in hydraulic simulations to verify that water is running downhill over the range of discharges



modeled. A typical example of a longitudinal water surface elevation plot is illustrated in Figure 2-5.

Figure 2-5. Simulated longitudinal water surface profiles.

The following terms are provided for completeness. They are treated in more detail in the specific sections on hydraulic models which follow. Additional terms and definitions related to hydraulic modeling can be found in Appendix 1.

Velocity Adjustment Factor (VAF): The ratio of discharge for which velocities are being simulated to the sum of simulated cell velocities times cell areas. VAF's are used to adjust simulated velocities to maintain mass balance for the simulated discharge. Interpretation of the VAF-discharge relation is discussed below in the section dealing with calibration and simulation of velocities.

Conveyance Factor (CFAC): The conveyance factor describes the ability of a cross section or cross section cell to transport (convey) water downstream. The standard conveyance factor formula for

U.S. conventional units is: $CFAC = (1.49 * Area * R^{2/3})/n$, where R is the hydraulic radius and "n" is Manning's n value. For metric units the 1.49 becomes 1.00. Since the conveyance factor at a cross section generally follows a power law relationship to discharge $CFAC = aQ^b$, the exponent can be determined from multiple discharge measurements at a cross section and used as a good initial estimate for the calibration parameter β in the MANSQ model as discussed below. Also called Water Transport Parameter (WTP) in the CALCF4 program output file.

Thalweg Slope : The change in elevation of the bed, measured at the point of maximum depth (i.e. thalweg depth) divided by the distance between cross sections. In PHABSIM, the thalweg slope may also be referred to as bed slope as shown in Figure 2-4.

Roughness (n): A coefficient indicating the resistance to flow or energy loss caused by the combined effects of particle size, vegetative friction, and channel features. In PHABSIM, this is most often expressed with the use of "Manning's n" values.

Stage of Zero Flow (SZF): The water surface elevation when water would stop flowing by a particular cross section. The stage of zero flow when measured in the field is usually the lowest ground elevation at a cross section when the cross section is at a hydraulic control. However, for some river features such as pools, the SZF is the lowest point of the streambed at the downstream hydraulic control for the pool. Because hydraulic controls can "migrate" with variation in discharge, measurement of SZF is difficult and is best done when flow is extremely low and water is not turbid. The determination of the proper SZF is discussed in more detail in the section dealing with modeling of water surface elevations using the STGQ program.

Equations Used For The Description and Analysis of Open-Channel Flow

Several fundamental equations and relationships are important to understand, since they constitute the computational basis for the various hydraulic models used within PHABSIM. A fundamental tenant of open channel flow is that continuity and mass balance of discharge must be maintained between adjacent cross sections for proper application of the hydraulic models. In addition, the overall energy balance due to friction losses between two adjacent cross sections must also be maintained. This is addressed in the hydraulic models within PHABSIM through the application of Manning's equation, which describes open channel flow in terms of measured cross section properties and relationships between the discharge, water surface elevation, velocity, and resistance to flow and the Bernoulli equation which evaluates longitudinal energy dissipation.

Continuity and Mass Balance

The water surface elevation in a stream defines the cross-sectional area of flow if the bed geometry is known. If mean cross section (channel) velocity is also known, discharge can be calculated using the equation of continuity (see Figure 2-3):

$$Q = AV \text{ (2-1) where: } Q = \text{discharge (cubic feet per second, cubic meters per second)}$$

V = average velocity of flow through the cross section (feet/second, meters/second)

A = cross section area of flow (square feet, square meters)

In practical applications, if no inflows or outflows occur within the study site and the water surface elevations do not change during the period of field data collection, the estimated or user-computed discharge for individual cross sections should yield estimates of the discharge that are alike for similar habitat types. Hydraulic data collection for a PHABSIM study is usually undertaken in habitat types important to fish and, therefore, some channel types that are not ideal for estimating discharge will be sampled. It is not uncommon that riffle habitats have discharges that are 10–20% higher than the discharge estimated in runs, which are more ideal in terms of estimating the “true” discharge. Conversely, discharge estimates in pools can typically be 10–20% lower than runs. When selecting the best estimate of discharge, users are encouraged to consider cross section conditions as a major determinant of the user-supplied “best estimate” discharge. For example, an average of the discharge measurements obtained from three run cross sections in a study site may be superior to an average of the flow measured at all cross sections.

Manning’s Equation

One of the most widely applied equations used to describe flow in open channels is referred to as Manning’s equation (p. 96 in Henderson, 1966). The equation represents an alternative formulation of Equation 2-1 in which site specific channel characteristics are incorporated in order to describe the resistance of flow within the channel given the roughness of bed material, energy slope, and channel geometry. For U.S. conventional units Manning’s equation is:

$$V = \frac{1.486 R^{2/3} S_e^{1/2}}{n} \quad (2-2)$$

where: V = mean channel velocity (feet/second, meters/second)

1.486 = U.S. conventional unit correction (cube root of 3.28 feet/meter), or a value of 1.0 for metric units

R = hydraulic radius, in feet (meters) S_e = slope of the energy grade line N = coefficient of roughness, referred to as Manning’s n

This equation, in several different formulations, is used within PHABSIM in the MANSQ and WSP models for the simulation of water surface elevations and in the VELSIM program for the simulation of velocities.

Energy Balance and the Bernoulli Equation

In Manning’s equation, the slope required as input is the slope of the energy grade line. This slope is defined as the difference in total energy at two (or more) channel sections, divided by the distance between them (refer to Figure 2-4). The total energy at a channel section is found with the open-channel form of the Bernoulli equation:

$$H = z + d + \frac{V^2}{2g} \quad (2-3)$$

where: H = total energy head, in feet (meters)
 z = elevation of the bed, in feet (meters)
 d = average depth for section, in feet (meters)
 V = average velocity in feet/second (meters/second)
 G = acceleration of gravity, 32.2 ft/sec² (9.8 m/sec²)

For practical purposes, Figure 2-4 shows that the term $z + d$ equals the water surface elevation (WSL) for a given cross section, therefore, the slope of the energy grade line can be determined by:

$$\frac{H_2 - H_1}{\Delta x}$$

$$S_e = (2-4)$$

If the assumption is made that flow in the channel is uniform, then bed slope, hydraulic slope, and energy slope are considered equal, $S_o = S_h = S_e$. Therefore, this equation represents the Energy Balance between two adjacent cross sections of the stream. The Bernoulli equation in conjunction with mass balance of the discharge and Manning's equation form the computational core to the WSP program as described later in this chapter.

Applied Modeling of Water Surface Elevations in PHABSIM

Determining the relationship between the water surface (stage) and the discharge is the first step in the hydraulic calibration and simulation phases of PHABSIM (Figure 1-2). The stage is used to derive depth distributions for each cross section by subtraction of bed elevations across the channel from the stage. It is also used to identify the location of the free surface to establish boundaries (i.e., wetted cell locations) for some of the equations that describe velocity distributions. If stage and bed elevation are known, depth may be determined at any location on the cross section. Stage varies with discharge, so it is important to derive a reliable relationship between stage and discharge for the study site or hydraulic simulation results will be in error.

There are three approaches for predicting stage-discharge relationships in PHABSIM. The approaches described in this section include: (1) linear regression techniques based on multiple measurements from the field (the STGQ model); (2) use of Manning's equation (the MANSQ model); and (3) calculation of water surface profiles using standard step-backwater computations (the WSP model).

In the PHABSIM for Windows interface, all three models are accessed under the **/Models/WSL** menu. To provide maximum flexibility in modeling water surface elevations, the interface allows the user to select different models for different discharges at individual transects. Thus, it is possible to mix modeling approaches (including supplying water surface elevations from an outside source) for individual transects in a project and across the full range of discharges. The selected WSL calculation method is entered in the table displayed in the **/Models/WSL/Method** tab. Other tabs provide for selection of options within each model and are discussed below and in the laboratories.

NOTE: Graphs may be viewed on screen from several tabs within the WSL modeling section. In the options tabs, the graphics aid in checking the appropriateness of input to the particular WSL model to be run. The **Cross Section** and **Longitudinal** buttons in the **/Models/WSL/Results** tab allow the user to view the results of WSL modeling. These plots are useful in calibration and quality control of the WSL simulation process.

Modeling the Stage-Discharge Relationship by Regression

One method of obtaining a relationship between stage and discharge is to measure the discharge at several stages and develop an empirical regression equation relating stage to discharge. In practice, typically three (MESC recommends three [3] or more) measurements of the stage and discharge are obtained at each cross section over as wide a flow range as practical or as necessary to meet the study objectives.

In a large number of channels, stage-discharge data of this nature has been found to be adequately approximated by the following equation:

$$(WSL - SZF) = a Q^b \quad (2-5)$$

where: Q = discharge

WSL = stage or water surface elevation

SZF = stage of zero flow

a = constant derived from measured values of discharge and stage

b = constant derived from measured values of discharge and stage

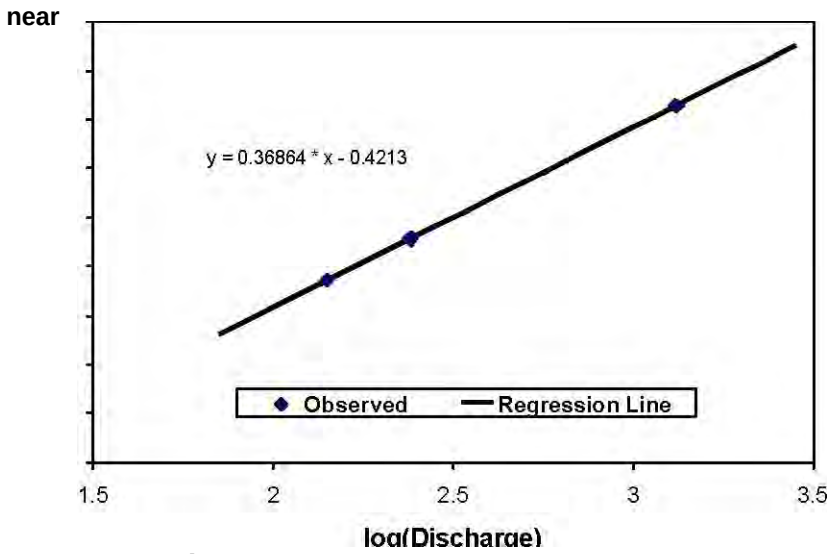
Note that we have included the SZF in Equation 2-5 since the stage-discharge relationship at a channel cross section is a function of the SZF at that specific location, as discussed below under the STGQ model. The SZF is used within the STGQ model and one option in MANSQ. It should be included whenever using alternative stage-discharge regressions. Equation 2-5 can be transformed to a linear relationship between stage and discharge by taking the log of the equation which yields:

$$\text{Log}(WSL - SZF) = \text{log}(a) + b * \text{log}(Q) \quad (2-6)$$

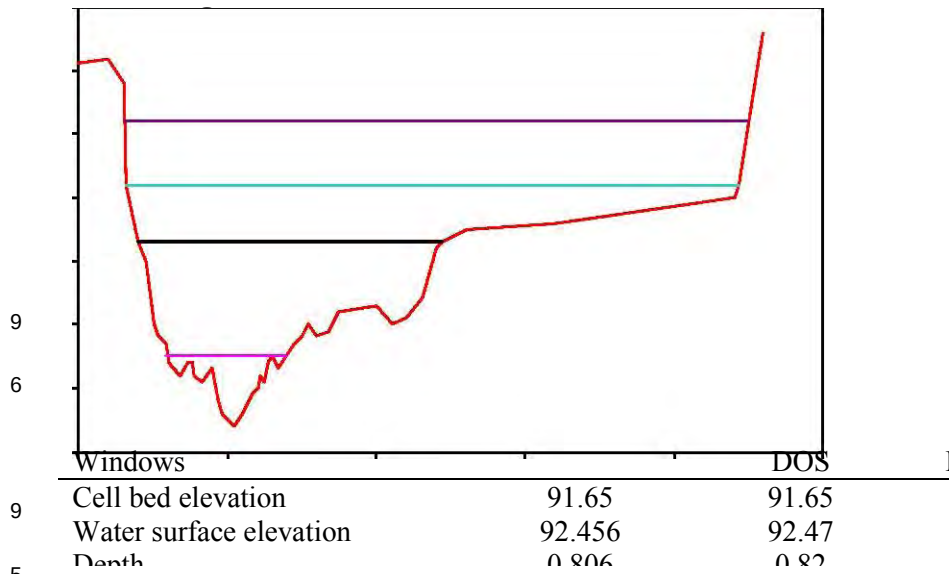
A simple linear regression can then be performed between the log of the discharge and the log of the water surface elevation (minus stage of zero flow) to determine the constants. The resulting regression equation is then used to predict stage over a desired range of discharges. An example of a measured stage-discharge relationship with the resulting regression equation derived from these data is given in Figure 2-6.

In some channels however, where complex geometry may result in a significant change in cross section area over a wide range in discharge as illustrated in Figure 2-7, or where a backwater effect from a downstream hydraulic control may occur, the stage-discharge relationship may not be log-linear as illustrated in Figure 2-8. In these instances, the user should take care to review the stage-discharge relation developed by the models in PHABSIM to ensure that the most accurate evaluation of the stage-discharge relationship is achieved. If the STGQ model is allowed to proceed normally, a single regression line will be derived from all of the data in the log-log domain as shown in Figure 2-9. In these instances, the analyst may choose to partition the data into multiple, piece-wise linear data sets and develop corresponding regression equations for specific ranges of discharges which are to be simulated as illustrated in Figure 2-10. In PHABSIM for Windows this can be accomplished by creating separate copies of the project for each regression range or by running STGQ for pairs of calibration flows and reentering the data in the methods table as fixed water surface elevations. Such two point lines have zero degrees of freedom and should be used for extrapolation with caution.

In addition, stage values may be generated entirely outside of PHABSIM and entered in the **/Models/WSL/Methods** table in lieu of running any of the PHABSIM models. Stage values entered in the **../Methods** table must be converted to normal domain; that is, one must exponentiate to remove the log conversion.



I
C
r
o
s
s



E
l
e
v
a
t
i
o
n

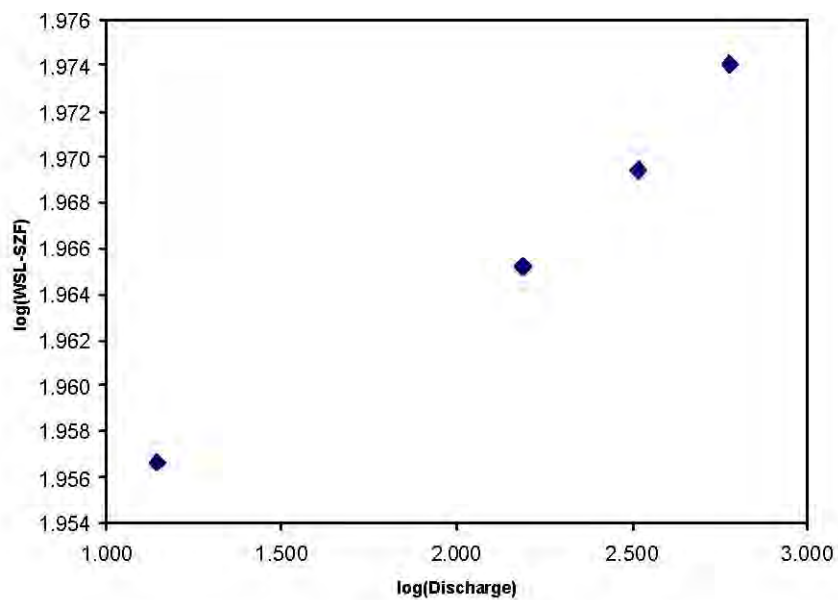


Figure 2-8. Log-log plot of stage-discharge for asymmetrical cross section above.

Stage-discharge Relationship

Stage-discharge Relationship

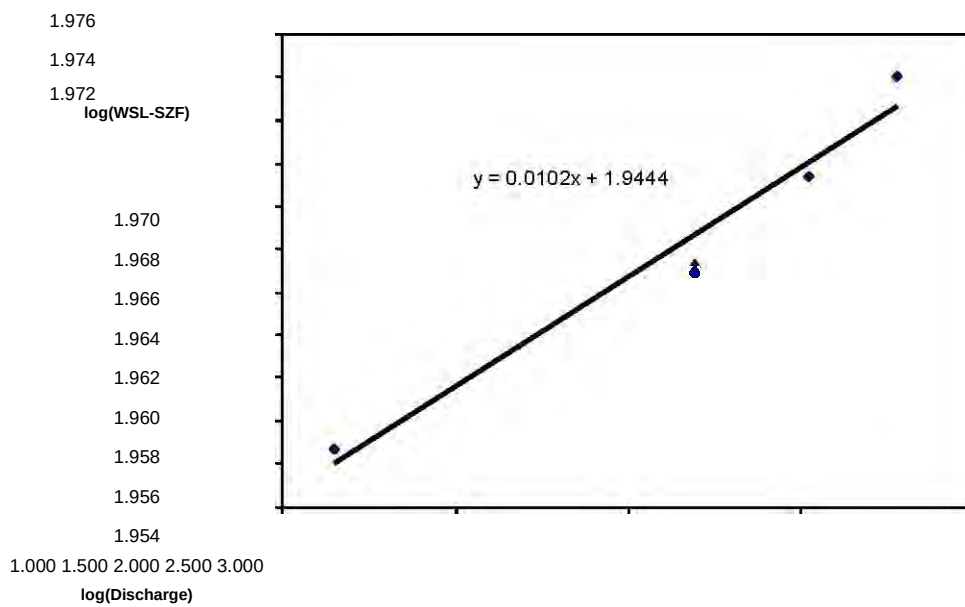


Figure 2-9. Default linear fit to non-linear stage-discharge data.

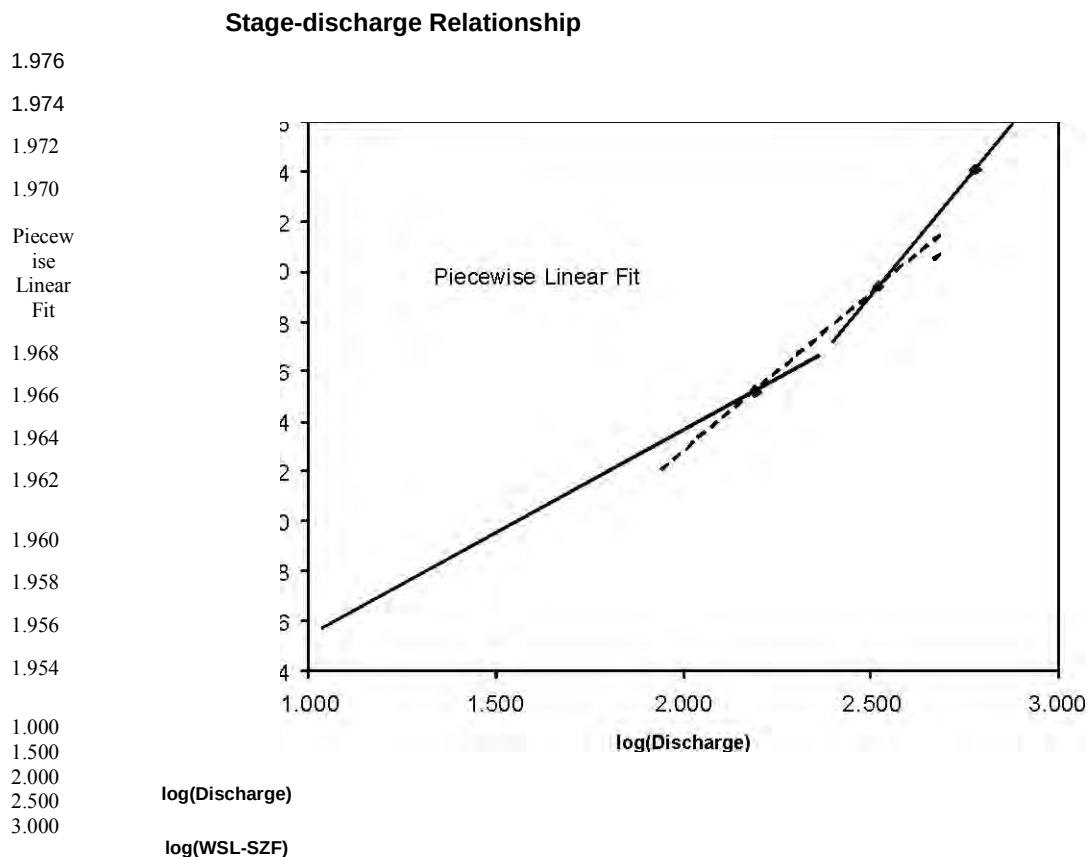


Figure 2-10. Multiple linear regression equations arranged to achieve a piecewise linear stage-discharge relation.

Alternatively, the user may also elect to fit a non-linear equation to the observed data for the purposes of modeling the relationship between stage and discharge as illustrated in Figure 2-11. It is advisable to use four or more points to allow for at least one degree of freedom in the regression. Non-linear fitting functions are available in various spreadsheet and statistical programs. The results may be inserted into PHABSIM as fixed WSL values in the methods table.

Regardless of whether the observed data is fit using a log-linear, piece-wise log-linear, or non-linear regression approach, the extrapolation of the regression equation to lower and higher discharge ranges than what was measured should be examined critically for reasonableness as discussed below. Upper and lower limits of extrapolated discharges are, to some degree, a matter of professional judgement and the specific analytical needs of a particular study. In general, the further away from the observed conditions, the greater the potential error between the actual stage and the stage predicted by extrapolation. The reasonable range of extrapolation varies among study sites so caution in extrapolation is advised.

Stage-discharge Relationship

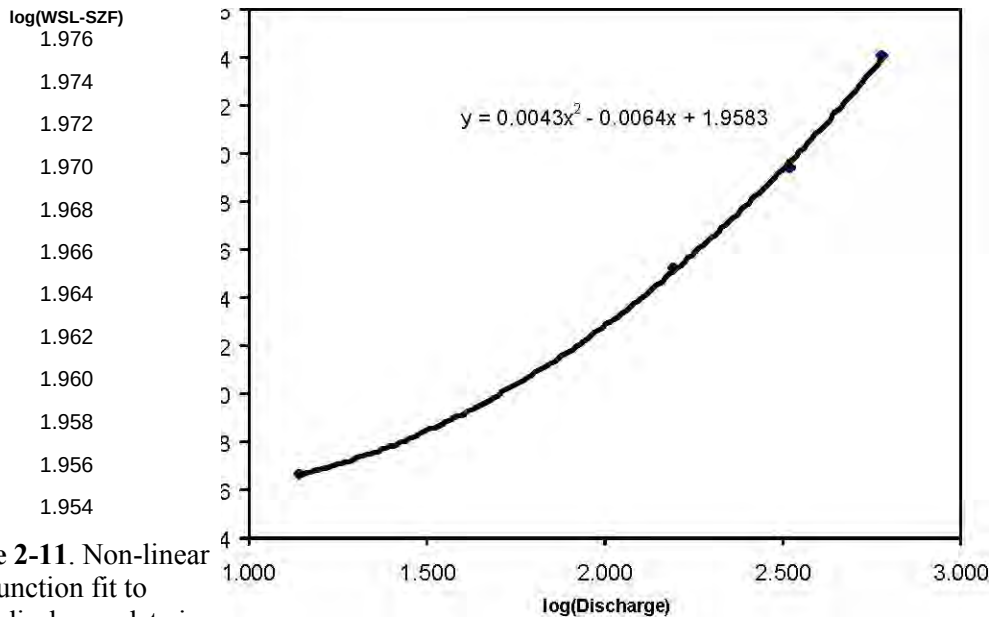


Figure 2-11. Non-linear function fit to stage-discharge data in logarithmic domain.

When using the regression approach, one should recognize that the regression equation developed for a specific cross section is independent of all other cross sections within a study site. Therefore, care should be exercised that internal consistency is maintained in the longitudinal profiles of the water surface elevations between adjacent cross sections within a specific study reach. For example, the results presented in Figure 2-12 show that the independent analysis of several cross sections using a log-linear regression approach (i.e., STGQ) results in the analysis predicting “water flowing uphill” for several discharges. Although the individual R^2 values of each regression were high (e.g., ≥ 0.95), longitudinal profile plots provide a simple diagnostic of model results that indicate an alternative modeling approach is required if the study requires simulating a range of discharges where water appears to flow uphill. Errors in water surface prediction will affect both the predicted depth and velocity values for this transect. Diagnostic evaluation of water surface modeling is discussed later in this chapter.

Determining the Stage of Zero Flow

Since the STGQ, and MANSQ models make use of the stage of zero flow (SZF) for computational purposes (see Equation 2-5 above and the MANSQ discussion below), it is important to understand how to obtain the proper SZF. The SZF is important since it is used directly in regression analysis of the stage-discharge equations in STGQ and in one simulation option within MANSQ. An error in estimating the SZF can alter hydraulic simulation results. The easiest way to determine the SZF is to plot the thalweg elevations at each cross section moving in an upstream direction as shown in the example provided in Figure 2-13.

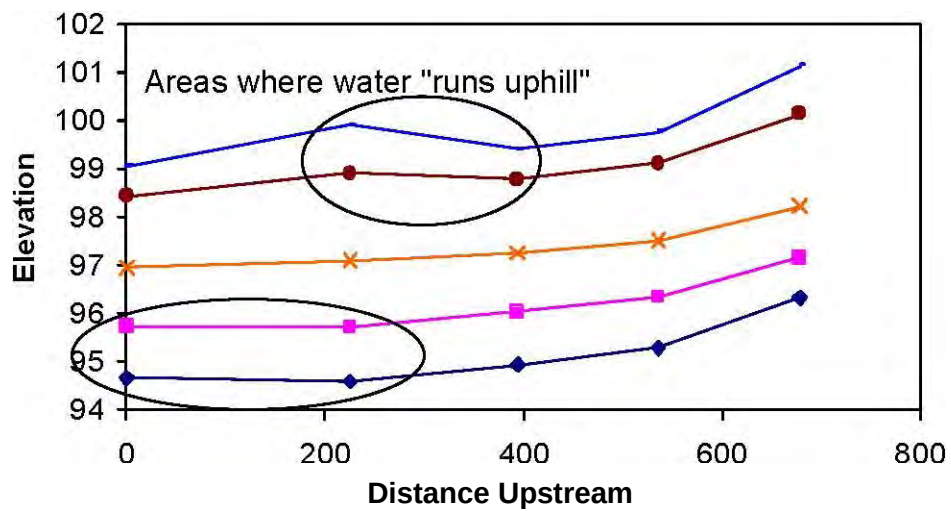


Figure 2-12. Independent stage-discharge analysis can result in a simulated adverse water surface profile.

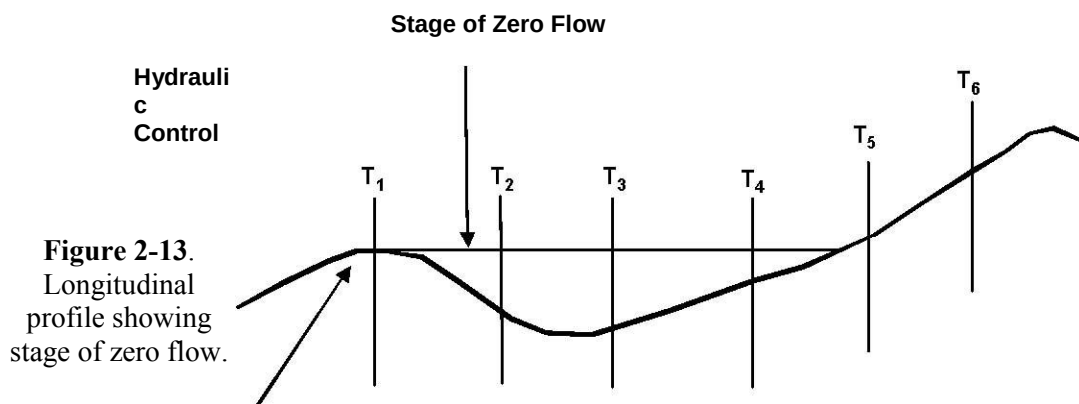


Figure 2-13. Longitudinal profile showing stage of zero flow.

As can be seen, the SZF at cross section T_1 corresponds to the thalweg depth at this cross section and will control the surface of the stream when the water level drops to this point. At that level, flow will cease, hence the concept of the stage at which zero flow will occur. It should also be apparent that this same SZF should be used at cross sections T_2 through T_4 since the elevation of the SZF at T_1 will control the water surface at these next two upstream cross sections. The individual thalweg depths should be used as the SZF at transects T_5 and T_6 .

Stage-Discharge Analysis using Regression in PHABSIM – the STGQ Model

The STGQ hydraulic simulation model predicts water surface elevation as a function of discharge. Given stage-discharge data, STGQ will automatically conduct the log-linear regression on the calibration data sets and determine the water surface elevations for all flows contained on the **/Edit/Discharges** table. When using the stage-discharge relationship, each cross section is treated independently of all others in the data set. This approach has the advantage that habitat areas from several locations in the stream (habitat mapping strategy) can be analyzed simultaneously. The principle disadvantage is that not all cross sections are well-suited for stage-discharge regression and the phenomenon of simulated adverse water surface gradients (see Figure 2-12) can occur. The STGQ program simulates water surface elevations using the stage-discharge relationship information supplied in the **/Edit/Cross Sections/ Calibration Data** tab in PHABSIM for Windows.

Running the STGQ Model

Once the STGQ model has been selected for a combination of cross sections and discharges in the **/Models/WSL/Method** table, the user selects options to be run for the study site in the **/Models/WSL/STGQ Options** tab. These selections are made by clicking on the model type, eg. **STGQ** and then clicking each of the transect/discharge boxes in the table to which that model is to be applied. The boxes will then contain the term “STGQ”.

Remember to review the output file **ZOUT** for error messages and inconsistencies in the data. (It will be the latest sequentially numbered ZOUT file in the directory where the project resides.) Error messages in the form of notes or other statements that do not appear on the screen or cause the program to abort may be written to the ZOUT file. Output from the STGQ model is variable depending on the selected simulation options. Examination of STGQ output is covered in the laboratory exercises.

STGQ Options

The user has the ability to select a variety of simulation and reporting options during the execution of the STGQ model. The associated laboratory exercises will address the use of the most commonly used options and, therefore, a detailed discussion of each option will not be presented here. Table 2-1 lists each of the options within STGQ and provides a concise description of the function for each option.

A Practical Guide to Modeling Stage-Discharge Relationships Using the Regression Approach

In most applications, the analyst will need to determine the “best estimate” of the discharge at a given calibration flow. Typically, the discharge calculated from observed velocity distributions may vary considerably between all measured cross sections. For example, it is not uncommon for the discharges computed within a single study reach in which the stage remains stable during field measurements to vary by as much as 25%. This is due to measurements being taken in pools, riffles, runs, etc. Generally, pools and riffles are poor areas for discharge estimation but are typically measured since they often represent critical habitat types necessary for evaluation as part of the instream flow investigations. Field crews should indicate during data collection which cross section(s) are best for estimation of the actual flow for a particular calibration set. The best discharge measuring sections are used to estimate the discharge for use in the regression analysis for all cross sections within the reach. The difference between the measured right and left bank water surface elevations can vary considerably with differences of 0.1 to 0.5 feet occurring in highly turbulent conditions. The analyst should select the average of the left and right bank, only the left or only the right, or other water surface elevation at each cross section in the regression equations based on the conditions reported in the field notes.

Table 2-1. Options in the STGQ program.

Option description	Action when set to indicated value
Prints the numerical details of the computed velocities and water surface elevations for each simulated discharge to ZOUT.	
Displays a table where the user assigns a CAL set to each discharge for each cross section.	
Discharge (IOC 5) (click cell, click down Selects whether the best estimate of the discharge arrow to change from Best Estimate of Q to or the discharge measured at this transect is used Xsec (transect) Q) in stage-discharge calculations. If no transect Q is supplied, defaults to best estimate.	
WSL (Click cell, click down arrow to change to Selects which of the WSL values supplied in Left, Right, Average or User supplied WSL) / Edit/Cross Sections/Calibration Data is used in WSL simulation.	
Selects if the stage of zero flow is used in the WSL simulation. Default is yes (checked).	

Output Options (applies to all WSL Simulation Models)

Selects which discharges are simulated in the current run. Default is all (all boxes checked).

The analyst also has the option of using the actual calculated discharges at each cross section in the regression equations rather than the best estimate for the reach. The analyst may also elect to vary the water surface elevations at a cross section within the range of measured differences between the left and right bank in attempts to get a better log-linear regression fit to the data. Using discharges other than the best estimated discharge or water surface elevations different than the average should be carefully considered; but, this choice does not imply errors in modeling as long as a rational basis for the use of alternative data is clearly articulated and justified in the study report.

In some instances, the flow rate will change during the course of field data collection at a study reach either within the day or between successive days for a variety of reasons. This is most often noted by changes in the stage readings of the water surface elevation during field data collection or during data processing where calculated discharges show a consistent increase or decrease between successive measurements. A typical approach with data sets having these characteristics is to derive best estimates of the discharge for groups of cross sections, which represent consistent field measurements under similar flow conditions.

For example, the first three cross sections measured during the first field day may have a best estimate of discharge equal to 100 cfs at the low calibration set while cross sections 4 through 7, collected the next day, may have a best estimate of the discharge of 120 cfs. Because the STGQ program treats each cross section as an independent data set, it has the ability to accommodate different discharges between cross sections for a given calibration set. In those instances in which the discharge changes during the collection of data at a single cross section, it is best to stop data collection until the flow stabilizes. However, if this is not an option, or this was determined in the office during review of data collection efforts, advanced modeling approaches beyond the scope of this chapter need to be undertaken. In those instances, the analyst should contact an experienced hydraulic engineer for technical assistance.

In summary, the following step-wise procedure can be followed for conducting stage-discharge modeling using the regression approach to estimate water surface elevations in PHABSIM.

1. Decide whether to use the best estimate of the discharge for each calibration set for all cross sections and whether to use the average of the right and left bank water surface elevations measured at each calibration flow. Be sure to check if the discharge remained constant during field collection efforts or whether different best estimates of the discharge need to be provided for different groups of cross sections. Finally, determine the appropriate stage of zero flow (SZF) for each of the cross sections.
2. Plot the log of the discharge versus the log of the WSL-SZF (**/Models/WSL/STGQ options/Stage Discharge Graph**) and examine the relationship for linearity or piece-wise linearity before proceeding. If the relationship at a cross section is not log-linear, consider an alternative modeling approach such as MANSQ or WSP or proceed with a non-linear analysis of the data (outside of PHABSIM for Windows) to predict the water surface elevations.
3. Ensure that all measured calibration data sets use the appropriate discharge and water surface elevations at each cross section and each calibration flow. Check that all such data are in the project file (See **/Edit/Cross Sections/Calibration Data**). When using a piece-wise linear approach, assign the Cal sets for a single “piece” and remove check marks from the rest to select the range of discharges you wish to simulate (**/Models/WSL/Output options**).
4. Run the STGQ model (Click **Run** under the **../WSL/Method** tab) and examine the longitudinal profiles (**Longitudinal** profile plot in the **../Results** tab) of the water surface elevations for all spatially linked cross sections to determine the quality of the model results.
5. If the longitudinal profiles look reasonable for all simulated discharges, proceed to the velocity calibration and simulation step of PHABSIM. If not, examine alternative WSL modeling approaches using MANSQ and/or WSP.

Review the output file ZOUTnn for error messages and inconsistencies in your data. Error messages in the form of notes or other statements that do not appear on the screen or cause the program to abort may be written to the output file. Output from the STGQ model includes a listing of the calibration data used in the stage-discharge regression, and the regression equation with diagnostic statistics for each cross section.

Modeling the Stage-Discharge Relationship Using Manning's Equation – The MANSQ Model

The MANSQ model can be used to determine the stage-discharge relationship for individual cross sections. The uniform flow assumption allows use of measured hydraulic slope instead of energy slope, since, by definition, they are equal if flow is uniform. In addition, this approach assumes that flow variations caused by changes in channel configuration are negligible (i.e., minimal backwater effects). Generally, the more uniform the channel, the more reliable the results using this approach, thus it is more reliable in run sections. The application of the MANSQ model in pools can sometimes be problematic since pools are generally created by backwater effects of a downstream hydraulic control. As was the case in using the STGQ model, the MANSQ model also assumes that each cross section is independent of all other cross sections during calibration and simulations. Therefore, as indicated for the STGQ program, the longitudinal profile of the simulated water surface elevations should always be checked to ensure water is flowing down hill between spatially linked cross sections in a study reach.

The MANSQ model uses Manning's equation in the form:

$$1.49$$

$$S^{1/2} R^{2/3}$$

$$Q = \frac{K}{n} A^{5/3} S^{1/2} \quad (2-7)$$

□

$$\equiv n \downarrow$$

and simplifies it to:

$$Q = K A_R^{2/3} S^{1/2} \quad (2-8)$$

The value of K is determined from one set of measured discharge and water surface elevation pairs and measured channel geometry at a cross section. The program then uses additional calibration data sets (i.e., discharges and water surface elevations) to solve one of the following three equations selected by the user:

$$\frac{Q}{Q_o} = \left(\frac{K}{K_o} \right)^\beta \quad (2-9)$$

$$Q$$

$$\leq \text{or} \geq$$

$$\left(\frac{R}{R_o} \right)^\beta$$

$$\left| \frac{1}{\log(2.42)} \right|$$

$$\left| \frac{1}{\log(2.42)} \right| \quad (2-11)$$

$$K = K_o$$

$$\left(\frac{R}{R_o} \right)^\beta \quad (2-10) \leq R_o \leq$$

$$5/3$$

$$\left(\frac{R_o}{R} \right)^\beta \left(\frac{R}{R_o} \right)^\beta \left(\frac{R_o}{R} \right)^\beta \left(\frac{R}{R_o} \right)^\beta$$

$$K = K_o \left(\frac{R}{R_o} \right)^\beta \log 2.42$$

$$R \geq \leq D50 \geq$$

$$\leq D50 \leq \leq \leq \geq$$

where: subscript o refers to calibration values,

exponent β represents a coefficient supplied by the user for each transect, and

D50 is the median particle size on the stream bed.

Selection of the ratio of discharges, the ratio of the hydraulic radius, or the empirical relation between hydraulic radii and median particle size is a choice made by the investigator. There is no strong evidence to suggest the discharge ratio is generally superior to the hydraulic radius ratio. Functionally, given multiple sets of discharge-water surface elevation data at a cross section, the user employs a trial and error procedure for selecting a value of β that minimizes the error between observed and predicted water surface elevations at the calibration discharges, regardless of which equation formulation is used. Due to the ease of switching between the first two

options, a trial-and-error approach may be used.

The third approach requires a sediment study to determine the median bed material size. This option cannot be used unless such a study has been conducted. When selecting the third option, the D50 value is entered in place of β (in the **/Models/WSL/MANSQ Options** tab). In all cases, the investigator should be able to justify the final calibrations by demonstrating minimum error between predicted and observed WSL at the calibration discharges.

The MANSQ β coefficients will typically be different for each cross section within a study reach. The range of the differences will depend on the variation in complexity of the channel at different cross sections. The range of β in typical applications is approximately 0.0 to 0.6; β cannot be less than 0. If calibrated β values fall outside this range, the results should be examined carefully, but such results do not necessarily imply that the data has errors or that hydraulic calibration is faulty. The investigator should examine the errors between predicted and observed water surface elevations in light of variations in cross section geometry and the observed ranges in discharge and water surface elevations. An average of several data sets evaluated at MESC yielded a β value of 0.22 for gravel bed channels. This may be a good starting estimate of β in the calibration process.

As previously noted, MANSQ treats each cross section independently. Therefore, once all cross sections have been suitably calibrated and the full range of desired discharges have been simulated, the longitudinal profiles of the water surface elevations should be checked for internal consistency (i.e., water flows downhill).

Running the MANSQ Model

Once the MANSQ model has been selected for a combination of cross sections and discharges in the **/Models/WSL/Method** table, the user selects options to be run for the study site in the **/Models/WSL/MANSQ Options** tab. You may find that by selecting only the desired calibration flows in the table in the **/Models/WSL/Output Options** tab during the calibration phase, calibration of the model is somewhat easier due to reduced amounts of output to evaluate. However, the user should ensure that after successful calibration of the model all flows of interest have been selected in **../Output Options** prior to performing the final WSL production run.

Remember to review the output file (latest ZOUTnn file) for error messages and inconsistencies in the data. Error messages in the form of notes or other statements may be written to the output file that did not appear on the screen or cause the program to abort. Examination of MANSQ output is deferred to the Laboratory exercises.

MANSQ Options

The user has the ability to select a variety of computational and reporting levels for the MANSQ program. The associated laboratory exercises will treat the use of the most commonly used options and therefore a detailed discussion of each option will not be presented here. Table 2-2 lists each of the options within MANSQ and provides a concise description of the function for each option.

Table 2-2. Options in the MANSQ program.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Option description Action when set to indicated value

Output Options (Applies to All WSL Simulation Models)

Use (check boxes for each discharge) Selects which discharges are simulated in the current run. Default is all (all boxes checked).

A Practical Guide to Calibrating MANSQ

The calibration of the MANSQ program involves a trial-and-error procedure to pick a β value that minimizes the error between predicted and observed water surface elevations at each transect. This can be summarized in the following steps:

1. Run **/Models/Water Transport Parameters (CALCF4)** by selecting that menu item. Use Notepad or Wordpad to view the **table.calcf4** file and search for the text string „WTP’ at each cross section. This is the conveyance factor. Locate the regression equation between discharge and the channel conveyance factor or water transport parameter (WTP) term for each cross section. The exponent (B) in the WTP regression equation is an excellent initial estimate for the β coefficient for each transect in the MANSQ program. Alternatively, just make a guess (i.e., 0.22) and proceed.
2. Select MANSQ options in the **/Models/WSL/MANSQ Options** tab. Then take care to select which calibration flow you intend to use as the initial calibration flow since this will represent a “fixed” calibration set for the program. The calibration sets are numbered in order of ascending discharge magnitude. Then select only the CAL set flows shown in **../WSL/Output options** , that is remove the checks from all but the calibration flows. Enter your best estimate for β at each cross section either derived from the WTP regression exponent term or your initial guess. Click **Run**.
3. Go to the **../WSL/Method** tab and select MANSQ for all transects.). Set the β coefficient at each transect (in the **../MANSQ Options** tab, change beta values in the table). Run the MANSQ program (**../Method** tab, click the run button). Compare the predicted versus observed WSL at each transect for all the calibration flows by moving to the **../Results** tab and noting WSL values in the table compared to observed values. The **Longitudinal** graph button in the **../Results** tab allows comparison of the observed and predicted WSL profile. Note that at the selected calibration flow the program will always return the given water surface elevation since this is an initial condition for determination of the K value at that discharge (see equations above). Change the β coefficient at each transect (**../MANSQ** tab, change beta values in the table) and repeat this process until the error between predicted and observed water surface elevations is minimized at all calibration flows. Remember each cross section is treated independently, so once one is calibrated, you can ignore it during the remaining calibrations of the other cross sections.
4. Once an adequate calibration is achieved, add all the flows of interest by checking the boxes in **../Output Options** and make the production run using MANSQ.
5. Check the predicted longitudinal profiles of the water surface elevations to ensure water flows downhill at all discharges.

As discussed in modeling water surface elevations with STGQ, the analyst can use the MANSQ program when discharges change between data collection efforts and/or cross sections. The calibration flows at each cross section or groups of cross sections are simply those used in the calibration process. Users may select different calibration flows for each cross section in the table in the **../MANSQ Options** tab. Similarly, the analyst can elect to use the computed discharge at each cross section rather than the best estimate of the discharge for the reach. Again, as long as a rational justification can be put forward and defended, these choices are a matter of professional judgement.

The reader is also encouraged to revisit the discussion in the section titled “A Practical Guide to Modeling Stage-Discharge Relationships Using Regression Approaches” provided above since many of the same situations will be encountered when applying the MANSQ model.

Modeling The Stage-Discharge Relationship Using A Step-backwater Approach – WSP

General Theory of the WSP Model

The WSP model is a water surface profile program that is used to predict how the longitudinal profile of the water surface elevation changes over a range of simulated discharges. Specific hydraulic relationships between the physical channel and discharge must be met to evaluate these changes in reference to a particular stream reach being modeled. These relationships are defined using concepts of mass balance (continuity) and energy balance. Several basic assumptions apply. These include assuming steady flow conditions existing during the period of field measurements and assuming boundary conditions remain basically rigid (i.e. the channel geometry does not change substantially over the range of measured data sets).

The following example illustrates the step-backwater computational process and introduces the relevant equations. In the example, two cross sections will be described which were illustrated in Figure 2-13. When more than two cross sections are involved, the process is repeated step-wise upstream; hence, the term step-backwater. The flow balance is calculated using the continuity equation:

$$Q_2 = Q_1 + \Delta Q \quad (2-12)$$

where: $Q_{1,2}$ = flow at each cross section as specified by the user ΔQ = specified change in flow (usually zero) between sections

The velocity is then calculated using the following equation:

$$V_i = \frac{Q_i}{A_i} \quad (2-13)$$

where: V_i = velocity at a cross section i A_i = area of cross section i Q_i = flow through cross section i

The energy balance is then calculated using:

$$H_2 = H_1 + \Delta H \quad (2-14)$$

where: $H_{1,2}$ = total energy at each cross section ΔH = total energy losses as water moves downstream

The total energy of the stream at a given cross-section is derived from the Bernoulli equation Chow (1959).

2

$$H = z + d + \frac{v^2}{2g} \quad (2-15)$$

where: z = elevation of channel bottom d = depth of water

$\frac{v^2}{2g}$ = energy component due to flow velocity (called velocity head) v = mean column velocity of water g = gravitational constant

The Bernoulli equation written in terms of two adjacent cross sections in the stream is therefore (see Figure 2-4):

$$\frac{V_1 V_2}{2g}$$

$$z_1 + d_1 + \frac{V_1^2}{2g} = z_2 + d_2 + \frac{V_2^2}{2g} - \text{losses} \quad (2-16)$$

$$\frac{V_1^2}{2g}$$

This equation accounts for the net effects of energy loss between two adjacent locations within the stream reach. Effects due to changes in bed elevation changes, depth, and velocity are accounted for by losses accumulated between cross sections and are accounted for within the WSP program.

An additional equation is used to relate energy and flow values so that the computational procedure can cross check between the flow and energy balances. Using the user-supplied data for discharge (Q) and roughness (Manning's n), and the calculated values for area (A) and hydraulic radius (R) from the measured data at each cross section, Manning's equation is used to define the energy slope S_{ei} at each location by:

$$S_{ei} = \frac{Q_i^2 n_i^2}{R_i^4 A_i^3} \quad (2-17)$$

where: Q_i = discharge (cfs, cms)

n_i = roughness coefficient

A_i = cross-section area (ft², m²)

R_i = hydraulic radius (ft,m), e.g., area divided by wetted perimeter

S_{ei} = energy slope (subscripts refer to any cross section i)

Manning's equation is empirical, and the roughness coefficient "n" is used to quantitatively express the degree of resistance to flow in the channel. The value of Manning's "n" is an indication of the roughness of the sides,

Windows	DOS	Difference	% difference
Cell bed elevation	91.65	0	0.00
Water surface elevation	92.456	0.014	0.02
Depth	0.806	0.014	1.71
Depth Suitability Index	0.0708	0.025	26.25
Combined Suitability Index	0.0644	0.023	26.25
Weighted Usable Area	8.698	3.096	26.25

bottom, and other irregularities of the channel profile. The value is used to indicate the net effect of all factors which resist the movement of water moving downstream through the channel. Typical values of Manning's roughness coefficient n in a natural river channel are given in Table 2-3 (derived from Henderson [1966]).

Table 2-3. Typical Manning's n values associated with channel types or conditions.

In the most general sense, the roughness or resistance to flow within a channel decreases with increasing discharge as illustrated in Figure 2-14. As can be seen the magnitude of Manning's n estimated for use in the model will be a function of the calibration discharge and will typically vary with simulated discharges according the general relationship shown in Figure 2-14.

This discharge-dependent change in roughness is accounted for in the WSP model by allowing the user to empirically determine this functional relationship and thus vary the Manning's n with discharge within the model

as described below. Under practical working conditions, Manning's n values may fall outside reported handbook ranges. This parameter in the model is attempting to integrate all kinds of resistance to flow that include "errors" in approximations such as fixed expansion and contraction coefficients, etc. Also, many of the cited handbook values are more indicative of high flow conditions. In addition, the presence of aquatic vegetation, for example, will result in much higher Manning's values than would be obtained at the same cross section in the absence of vegetation. The overriding principal in the application of the WSP model and, in particular, deriving Manning's n values is whether or not the model adequately predicts the observed water surface elevations.

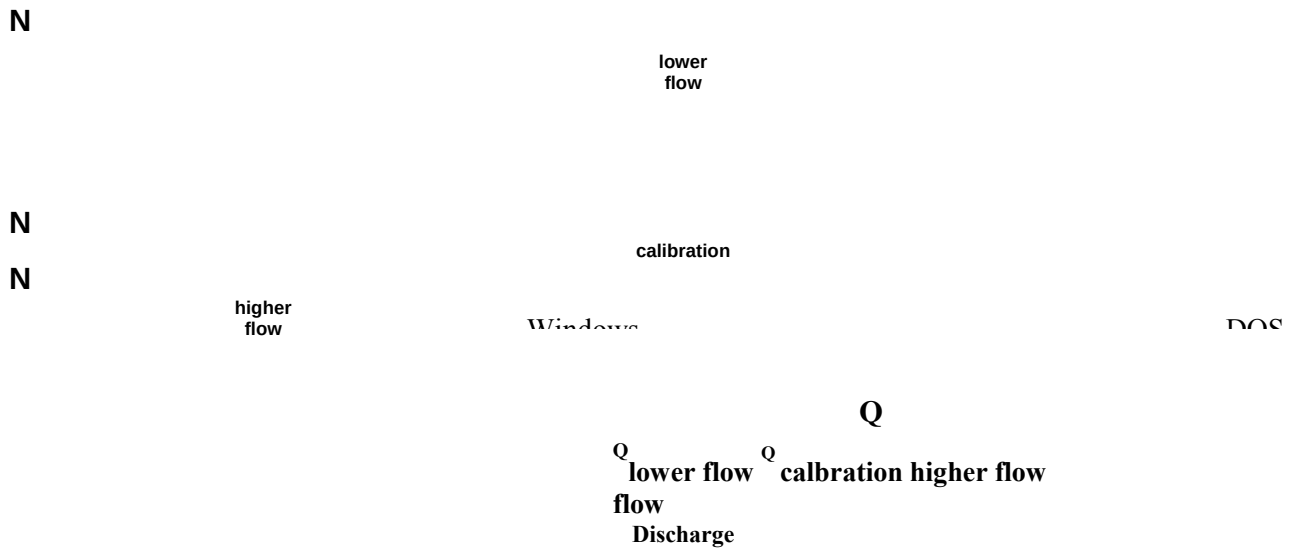


Figure 2-14. Change in roughness magnitude with discharge. Computational Process of the

Step-Backwater Approach to Water Surface Modeling The basic step-backwater approach to compute water surface profiles proceeds as follows:

1. Starting at the farthest downstream cross section, a water surface elevation (WSL_1) is taken from user-supplied values or calculated from the user-supplied energy slope using Manning's equation.
2. The energy slope for cross section 1 (S_{e1}) may be calculated from Manning's equation if water surface elevations are supplied or may be used directly if energy slopes are supplied. (Values of A , R , and V are determined from channel geometry, WSL , and flow.)
3. The water surface elevation at the next cross section (WSL_2) is estimated by projecting S_{e1} upstream over the distance (L) between the two cross sections.
4. The energy slope at cross section 2 (S_{e2}) is calculated using Manning's equations and an average slope for the section is determined from:

$$S_e = \text{function} \\ (S_{e1}, S_{e2}) \\ (2-18)$$

$$Q_2 = Q_1 \text{ (2-19)}$$

5. Flow and energy balances at the two cross sections are performed using:

$$H_2 = H_1 + S_{eL} + (\text{other losses}) \text{ (2-20)}$$

where: $Q_1 = Q_2$ = steady flow at both cross sections
 H_1, H_2 = total energy at both cross sections
 S_{eL} = energy losses over the distance L

Other losses associated with effects such as expansion and eddy losses are calculated within the program.

6. The water surface elevation at the second cross section is calculated by removing the velocity head from the total energy head yielding:

$$\frac{V_2^2}{2g}$$

$$WSL_2 = H_2 - \frac{V_2^2}{2g} \text{ (2-21)}$$

1. The WSL_2 values from steps 3 and 6 are compared and a numerical technique is used to adjust the estimated WSL_2 values.
2. Steps 3 through 8 are repeated until there is close agreement between estimated and calculated water surface elevations.
3. The entire process is repeated for cross sections 2 and 3, 3 and 4, and so on until all cross section are processed.

Users should note that the computed water surface elevations may not agree with those measured in the field even though internal agreement may be obtained within the WSP model. In this situation, the value of Manning's n is changed by the user and the program is rerun until the energy-balanced water surface elevations calibrate with observed water surface elevations at the single calibration flow. After this initial calibration is achieved, the additional calibration data sets are used to empirically derive the relationship between roughness and discharge illustrated in Figure 2-15 for use in the model as described in the following sections.

WSP Options

The user has the ability to select a variety of computational and reporting levels during the execution of the WSP program. The associated laboratory exercises will treat the use of the most commonly used options in WSP and therefore, a detailed discussion of each option will not be presented here. Table 2-4 lists the options within WSP and provides a concise description of the function for each option. Although various hydraulic options were provided in the original WSP program, most of them have a limited applicability to PHABSIM studies. Thus, the options available in PHABSIM for Windows are limited to those relevant to habitat studies. For a detailed explanation of these options, the reader should consult a "Guide to the Application of the Water Surface Profile Computer Program" (U.S. Bureau of Reclamation, 1968).

Table 2-4. Options in the WSP program.

Option description Action when set to indicated value

Use Critical Discharge Forces water surface elevation to be at critical flow elevation if Constraint (check box) supercritical flow is detected. (Strongly recommend checking this box for most applications.)

Override Error Processing Overrides certain error processing by overriding the limit on the (check box) allowable change in energy loss between two sections. WSP will not calculate the upstream water surface elevation if the change in elevation is too large and will not proceed further. Sometimes it is useful to review the results with a large change in water surface elevation between two cross sections to find the cross section(s) where the problem occurs. Suggest production runs should be made with this option off as the underlying problem should be dealt with first.

Write cell details (check box) Writes cell calculation details to ZOUT.

Set “n” values (table) N values are entered for each cross section and the entries revised to achieve calibration.

DD” (table) Transect roughness modifiers are supplied to adjust n as a function of discharge.

Output Options (this Applies to all WSL Simulation Models)

Use (check boxes for each Selects which discharges are simulated in the current run. Default discharge) is all (all boxes checked).

A Conceptual Overview of WSP Calibration

Calibrating the Longitudinal Water Surface Profile

We begin by recalling that WSP assumes the cross sections are connected and contiguous within a study site. Then, from an applied perspective, the first calibration step in WSP involves the estimation of an appropriate Manning’s n value for the entire study site (that is, the same n is supplied for each cross section) which minimizes the error between observed and predicted water surface elevations at the selected discharge. In other words, the user selects a Manning’s n value for all cross sections which allows the WSP model to approximate the observed longitudinal profile of the water surface elevation at all cross sections at this initial (or base) calibration discharge. Normally an increase in the roughness coefficients increases the predicted water surface elevation and a decrease in Manning’s n usually reduces the predicted water surface elevation. The first phase of calibration consists of setting n for all cross sections, running WSP, evaluating the results, and adjusting n until suitable agreement between observed and simulated water surface elevation is achieved.

Note that the water surface elevation (or slope) at the downstream-most cross section is a given input to the model and as such, is not part of the actual calibration of WSP for the first cross section. If the user has not measured the starting water surface elevations for all flows of interest and for which the WSP program will be used, then either the STGQ or MANSQ model (or other suitable approach) must be used to generate the starting water surface elevations at the down stream cross section.

One can provide an initial estimate of the Manning's n value using handbook values based on the observed channel configuration and substrate characteristics (e.g., see Table 2-3, or [Chow, 1959]), however, the following technique provides a means of adjusting Manning's n that empirically reflects the dynamics of the resistance to flow based on field measurements.

Begin by using the observed WSL and an initial estimate (obtained from handbooks or by professional judgement) for the Manning's n value for the study site (a global value for all cross sections) and run the WSP model. Examine the output and record the average value of the computed slope obtained over the entire study site (see Equations 2-16 and 2-17, above).

Treating the initial estimate of Manning's n and computed slope from WSP as "trial" values, along with the actual average measured slope for the study obtained from field measurements, the following equation will yield an adjusted estimate of Manning's n for the study site.

$$n_{\text{needed}} = n_{\text{trial}} \left(\frac{S_{\text{computed}}}{S_{\text{measured}}} \right)^{1/2} \quad (2-22)$$

This value can be substituted for the initial trial Manning's n value for all cross sections. The WSP model can then be re-run to evaluate the overall fit of the simulated water surface profile. The user should not expect that the n selected will result in a "perfect" match of all observed WSL's at all cross sections. When an apparent best fit has been obtained, proceed to "Calibration of WSP to Additional Longitudinal Profiles", below.

Calibration of WSP to Additional Longitudinal Profiles using Roughness Modifiers (RMODs)

In this calibration step, the relationship between discharge and roughness observed in open channels illustrated in Figure 2-15 is derived empirically. Since the roughness varies as a function of discharge, some means must be used to take into account the changes in roughness with discharge. Therefore, the Manning's n values obtained in the first step of the calibration must be modified appropriately in order to reproduce the observed longitudinal water surface profile at other calibration discharges. The objective is to select roughness modifiers so the new roughness (i.e., computed Manning's n values used during program execution) minimizes the error between observed and predicted longitudinal profiles of the water surface elevations at the remaining calibration flows.

To accomplish this step of the calibration, the remaining calibration discharges and starting water surface elevations (or slopes) at the downstream-most cross section are provided to WSP using the table in the **/Models/WSL/Method** tab. The user then uses a trial and error procedure to select appropriate roughness modifiers for each new calibration flow which minimize the error between predicted and observed water surface elevations for all cross sections at each of the new calibration flows. Note that the RMOD value for the initial (or base) calibration discharge used during the first step for calibration of Manning's n is 1.0 and should remain so for all simulations. The "base" condition represents our starting point for adjusting n as a function of discharge so it should be multiplied by 1.0 to preserve the starting point. Once the appropriate roughness modifiers associated with the other calibration discharges have been obtained, experience has shown that the roughness modifiers vary approximately with discharge as shown in Figure 2-15, which can be represented by a power law equation:

$$\text{RMOD} = a Q^b \quad (2-23)$$

The coefficient and exponent can be empirically determined from a linear regression between the logarithm of the RMODs and the logarithms of their associated calibration discharges. This regression equation is then used to derive the appropriate RMODs at all flows of interest to be simulated with the WSP model and entered along with the starting water surface elevations (or slopes) at the downstream cross section. A linear regression for RMOD values can easily be performed in a spreadsheet and is not included in PHABSIM for Windows.

The user should not expect that the RMODs will result in a “perfect” match of all observed WSLs at all cross sections for the remaining calibration discharges. The final selection of a particular RMOD value for a given calibration flow will be based on an attempt to minimize the error between predicted and observed WSLs between all cross sections at a particular calibration flow. Often, for example, one will accept a larger error at some cross sections to preserve a better fit over the entire study site and range of observed discharges. This will require the analyst to exercise some degree of judgement which must have a rational basis in light of the conditions at the study site and the needs of the particular study.

PHABSIM for Windows provides effective graphical tools for n calibration. Viewing longitudinal profile graphs in the **/Models/WSL/Results** tab can give a quick visual comparison of calculated and observed water surface values at each transect. Adjustments to n and RMOD values can be made and the WSP model re-run rather quickly, so a trial-and-error procedure for n and RMOD calibration is both feasible and timely.

Adjusting n Values for Individual Transects

It is tempting to adjust n values to obtain an exact match between measured and simulated water surface elevations at your selected “base” calibration discharge. While visually appealing, such a practice can: (a) maximize the impact of any measurement errors, and (b) result in a poor fit to measured water surface profiles at other measured discharges. If there is a poor fit at the other measured discharges, the analyst cannot be confident about the quality of the simulated water surface profiles obtained using widely varying Manning’s n values. In short, if n must vary over a wide range to obtain an exact match to the measured water surface profile at the calibration discharge, something is very wrong. *Such a practice is strongly discouraged.*

Instead, using different n values among cross sections at a study site should be based on some assessment of changes in the physical conditions among the cross sections. Such changes typically include variation in the bed material (where n represents bed particle roughness, e.g., friction) or in the channel configuration or bed form (where n also incorporates form roughness).

Because Manning’s equation does not differentiate between the types of roughness described by n, the user must supply (and defend) the rationale for varying n among cross sections. The initial “global” n approach captures the overall resistance to flow of the channel within the study site. Then, local variations in n may be considered where there is some physical justification. For example, if there is an area with large numbers of colluvial boulders in the stream, the boulder field would be expected to have a higher-than-site-average flow resistance. Other areas would be likely to have resistance below the average. Similarly, changing from a rectangular cross section in a riffle to a parabolic cross section in a pool may justify small local adjustments to n by trial and error. In general, adjustment of n values for individual cross sections more than approximately ± 0% ~15% of the global value for the study site needs to be justified by specific evidence about large changes in bed material or channel configuration. Whenever making local n adjustments keep two criteria in mind: (1) there must be some physical basis and (2) the adjustment is intended to obtain a better match between predicted and observed water surface profiles. If an adjustment made to obtain a better water surface elevation match is contrary to the apparent physical processes in the channel, it cannot be defended.

Note that the Manning's n value at a downstream cross section can have an "impact" on the magnitudes of the Manning's n values at the remaining cross sections. During the calibration procedure, care must be taken to avoid a see-saw effect in selected n values.

Determining Initial Water Surface Elevations for Calibrated WSP Models

The final required step for using the calibrated WSP model for WSL simulation is to define the starting water surface elevations at the downstream cross section for all unmeasured flows. The most common approaches are to use either a stage-discharge regression (STGQ model) or Manning's equation (MANSQ model). In both of these instances, the user can instruct the PHABSIM interface to extract the water surface elevations for a single cross section from the existing STGQ or MANSQ results by selecting the **WSP/STGQ** or **WSP/MANSQ** methods for the downstream-most cross section in the **Models/WSL/Method** tab. It is highly recommended that practitioners place the downstream-most cross section on a hydraulic control. This enables use of the STGQ or MANSQ model to establish starting WSL's for unmeasured discharges at the control cross section. Use of either STGQ, MANSQ, or another source of the initial conditions for backwater modeling, is the analyst's responsibility. The predictions of the water surface elevations produced by STGQ or MANSQ are transferred to the WSP model by the PHABSIM interface when the WSP/STGQ or WSP/MANSQ options are selected. If the water surface elevations for unmeasured discharges are obtained from an outside source, the user may enter those values using the **WSP/User supplies initial WSL** option in the **Models/WSL/Method** tab.

Regardless of the method used to supply initial WSP water surface elevations, the user must set appropriate RMOD values for all discharges prior to use of WSP for production runs. As stressed previously, the user should then check the overall quality of the hydraulic simulations by checking the longitudinal water surface profiles over the full range of simulated flows.

A Step-by-Step WSP Calibration Strategy

The WSP program is used most often in those instances where multiple stage-discharge measurements are available. The following approach is provided as a guideline to calibrate the WSP model.

1. Select WSP as the water surface profile simulation method in **/Models/WSL/Method**. Note the downstream cross section must have an entry of **WSP/STGQ**, **WSP/MANSQ**, or **WSP/User supplies initial WSL** and that the MANSQ or STGQ models must have been calibrated for the downstream cross section where WSP will be used. Supply an RMOD value for each discharge in the **./WSP Options** tab. Initial RMOD values can all be 1.0.
2. Run the WSP program and examine the results and ZOUT files to find the computed slope for the downstream-most cross section and use Equation 2-22 or trial-and-error to estimate a revised Manning's n value for the study site. Edit the cross section data so the all cross sections have this Manning's n value. Note: an error message: "WSP Terminated with an Unknown Error" usually indicates you did not supply an RMOD value for each discharge.
3. Re-run the WSP model and note the agreement of predicted WSL with observed values at the base discharge. Based on the difference between predicted and observed WSL, adjust the global Manning's n value for all cross sections and re-run the WSP model. Continue to change the Manning's n value until the predicted and observed water surface elevations are as close as can be obtained with the global n applied to all cross sections. Some variation between the observed and predicted WSL values is likely to occur at some transects. But the overall error should have been minimized.
4. Adjust local (cross section by cross section) n values (within $\pm 10\% \sim 15\%$) to reduce the remaining error between the observed and predicted water surface profile. Make those adjustments with the physical processes in mind and avoid adjustments that cannot be physically justified, i.e., do not "curve fit". Evaluate if the agreement error is within the tolerance limits that meet your study objectives. Remember, the WSP model works in an upstream manner and therefore the predicted WSL at the second cross section will be the starting WSL for making the predictions of the WSL at the third cross section, and so on proceeding upstream. For example, a low predicted WSL at the second cross section will "start" the model lower than wanted while

attempting to reach the WSL at the next cross section. This can result in supplying unusual Manning's n values at the next upstream cross section in order to get agreement at that cross section. The user should also note that in many instances, exact agreement is not always possible and WSLs at some cross sections may be high while at others they will be low. Again, some level of professional judgement, based on experience, will be necessary in order to determine how close predicted versus observed water surface elevations must be to be acceptable for individual cross sections or for all cross sections. Once suitable agreement between predicted and observed water surface profiles has been obtained for the base discharge, proceed to step 5.

5. Once the initial longitudinal water surface profile has been calibrated by selecting the appropriate Manning's n values at each cross section, broaden the evaluation to include the remaining calibration discharges and starting water surface elevations at the down stream cross section. Select the other calibration discharges in **/Models/WSL/Output Options**. Initially the roughness multipliers (RMODs) for these new calibration flows can be set to 1.0. Or, based on whether the other calibration flows are higher or lower than your initial calibration flow, you can set the RMODs to be greater or less than 1.0 based on the relationship shown in Figure 2-15. New calibration flows greater than your initial calibration flow will require a Manning's n lower than 1.0, while new calibration flows lower than the initial calibration flow will require a Manning's n greater than 1.0. The relative magnitudes of the RMOD estimates will be a function of how different the magnitude of the discharges are relative to your initial calibration flow.

- 6: Re-run the WSP model with the new roughness modifiers and compare the predicted and observed WSL at all cross sections at these new calibration flows. Adjust the RMODs at the new calibration flows until suitable agreement between predicted and observed water surface elevations are obtained. Each discharge is computed independently within WSP so once an RMOD is found which works for a specific calibration flow, that RMOD can be left unchanged while continuing your work at the remaining calibration flows. RMODs should be adjusted to obtain an overall minimum error between predicted and observed WSL for all calibration discharges.
7. Perform a linear regression between the logs of the RMODs and the logs of the discharge and use this equation to estimate the RMODs for all flows of interest for the study that you plan to use the WSP model to predict the water surface elevations.
8. Use the STGQ program or MANSQ program to supply initial WSL's to WSP at the most downstream transect for all other discharges to be simulated. That is, use **WSP/STGQ** or **WSP/MANSQ** at the WSP starting transect in the **Models/WSL/Method** tab. Remember a starting water surface elevation must be specified for all flows of interest at the first or downstream-most cross section when using the WSP model. If the STGQ or MANSQ models are used for WSP initial conditions, those models must be calibrated first before proceeding with WSP.
9. Add any additional desired discharges to the PHABSIM project using **Edit/Discharges**. RMODs determined from Step 7 must be associated with each of these flows (see the **WSP Options** tab) and the water surface elevation simulation must have those discharges specified in the **Models/ WSL/ Output Options** tab.
10. Check the quality of the hydraulic simulations by plotting the longitudinal profiles of the water surface elevations for all simulated discharges (use the **../Results/Longitudinal** graph button). Zoom in on the calibration discharges for one last comparison of the predicted and observed water surface profiles and make any final adjustments to n or RMOD as needed. If the very highest discharges produce unusual water surface profiles, check for predicted water surface elevations higher than the highest measured bed elevations. The model becomes invalid if WSL's significantly greater than the highest bed elevation are predicted. If such high discharges must be simulated, more field data is needed to define the channel at those heights.

Some Practical Aspects of Calibrating and Use of the WSP Model

The quality of calibration that can be obtained for a stream section will vary with the hydraulic characteristics of the stream and the nuances of the field data. Steep, rough streams often exhibit large fluctuations in water velocities and water surface elevations and may be difficult to calibrate. Typically, achievable agreement between observed and simulated water surface elevations is $\pm 0.01\sim 0.02$ feet ($\pm 0.00305\sim 0.0061$ m) for the profiles at each calibration discharge. However, the investigator must be aware that specific situations may require establishment of more lenient or stricter standards. For example, an investigator may relax this standard somewhat at the highest calibration flow profile in order to achieve a closer agreement at the middle and lowest calibration flow profiles since this lower range of discharges is most important in view of the particular instream flow project under consideration.

Although text book values of Manning's n can serve as a reference point, it should be noted that many of these values are most appropriate for higher discharges at or near bank full conditions and as illustrated in Figure 2-15, may, in fact, be too low under lower flow conditions. In other words, do not be surprised if the calibration Manning's n values do not match the ranges reported in the hydraulic handbook values. This should not be a source of concern as long as a physically based meaning can be attached to the values. Perhaps the most critical factor should be how well the model is able to reproduce the observed data. This of course assumes that any obvious data collection and entry errors have adequately discounted or corrected.

The WSP model will produce unreliable results if water surface elevations significantly higher than the highest cross section elevations are necessary to simulate the desired discharges. Always review the longitudinal profile for realism of the simulation. When very high discharges must be simulated as part of a PHABSIM study, it is imperative that at least bed elevations high on the bank and water surface elevations for a discharge in the vicinity of the desired high discharge be collected to ensure the PHABSIM models can run within reasonable bounds.

Hydraulic Controls

Transects should start and end at hydraulic controls if at all practical. Calibration problems are greatly exacerbated when starting and ending transects are not located at hydraulic controls. The effect of hydraulic controls in a WSP calibration are often profound. It is often possible to alter the water surface profile through an entire reach simply by modifying the roughness at the downstream control. One overriding principle of the WSP model is that the downstream-most transect must be on a control and all other controls in the reach should be defined by a transect. This means the downstream control associated with specific habitat features, such as a pool, should be included even if they are of no interest for representing the habitat feature of interest.

Divided Flow

Flow partitioning is a necessity when the channel around one side of an island is longer than the other side. When the length of one channel exceeds the length of the other by a factor of approximately 1.5 or more, or the channel configurations differ significantly, flow partitioning should be considered. In essence, flow partitioning involves breaking up the total discharge of the stream into component discharges for each channel. The WSP program is calibrated for each channel at the component discharge as if it were a separate stream (see below). At the calibration discharge(s), this is a relatively easy procedure because field notes should contain all the information needed to break out component discharges. The problem arises when alternative stream flows are modeled. At discharges other than the calibration discharge(s), the proportion of the total flow carried by either channel changes as a function of total discharge. The process of flow partitioning often is very difficult. It is advisable to consult an experienced hydraulic engineer before attempting this type of analysis. Basically, the problem is to determine the component discharges at a range of unobserved flows so that a rating table can be built. This is done by first calibrating the component channels as measured; then for some unobserved total discharge, component flows for each side channel are split out by estimation and run individually through the model.

Calibration of the WSP model can be difficult when flow splits into two or more channels. In general, the water surface elevation models in PHABSIM are not designed to work in split channels. A few streams may have small enough differences between channels on either side of an island to follow one of the transect placement or data adjustment approaches described below. However, in most cases, those approaches will introduce considerable error. MESC recommends users partition the flow empirically through each of the channels and treat each channel as if it were a separate stream to be calibrated and simulated separately. This means that discharge measurements for the full channel and each side channel must be made for at least the calibration discharges. A regression of side channel discharge against full channel discharge (or other means to build a rating table) can then be used to determine the flow split for the unmeasured discharges to be simulated in the study.

When partitioning the flow, care must be taken to ensure that the water surface elevations simulated at the top of each separate channel are the same (or within an acceptable tolerance) for all discharges. This allows an island to be represented by four backwater models: main channel downstream of the island, left side channel, right side channel, and main channel upstream of the island. A backwater simulation can be run for the main channel downstream of the island to produce the starting water surface elevation for both side channels for all discharges of interest. Then the two side channels are simulated with Manning's n calibrated to produce the same water surface elevation at the top of the island. And finally, the main channel upstream of the island is simulated using the initial water surface elevations derived for all flows from the simulation of the two side channels. In PHABSIM for Windows, this will require four projects covering the four separate portions of the channel and ensuring that the transects at the partitions are duplicated in the appropriate data sets. Though tedious, this is the only way to assure that the flow conditions around the island are modeled accurately over a wide range of discharges.

When there are small differences between the two channels around an island and the study site is represented with a single backwater model, two generic types of problems are presented by divided flow. The first, and most common, is unequal water surface elevations on both sides of a flow division. The most common cause of this problem is crossing an island with one straight transect when a dogleg transect should have been used (see Figure 2-15). By their very nature, islands rarely have the same bed and water surface elevation at equidistant points along the bank. Ideally, the transect should cross the island with a dogleg in order to obtain an equal water surface profile on both sides of the island. In braided channels, this is the rule rather than the exception. The two elevations may be averaged if the discrepancy between two water surface elevations is small compared to the difference in elevations between transects for all calibration flows. What constitutes small in this instance is a matter of judgement. However, if the discrepancy between water surface elevations is large, bed elevations of the smaller channel may be raised or lowered a distance equal to the difference in water surface elevations. All of these manipulations of the data may introduce their own noise in the analysis. Again, splitting the study site into four backwater models is preferred.

The energy loss between the two channels must be the same for water surface elevations to equalize at the head of the island. The two component flows giving the same energy loss for both channels (which should equal the total flow in the channel) are the proper component flows. If finding flow rates and energy losses that satisfy these conditions seems extremely tedious and difficult, it is! Alternatively, such ratings can be built empirically by collecting both water surface elevation and discharge data at several flows over the range of discharge of interest to the study. Hence, if you have split flow, plan on making many more water surface and discharge measurements in both the main channel and side channels.

Water Surface is Equal on Both Channels

Running the WSP Model WSP must have starting conditions supplied at the downstream-most transect to which it will be applied. In the /Models/WSL/Method table select either **WSP/MANSQ**, **WSP/STGQ**, or **WSP/Supplied** for the

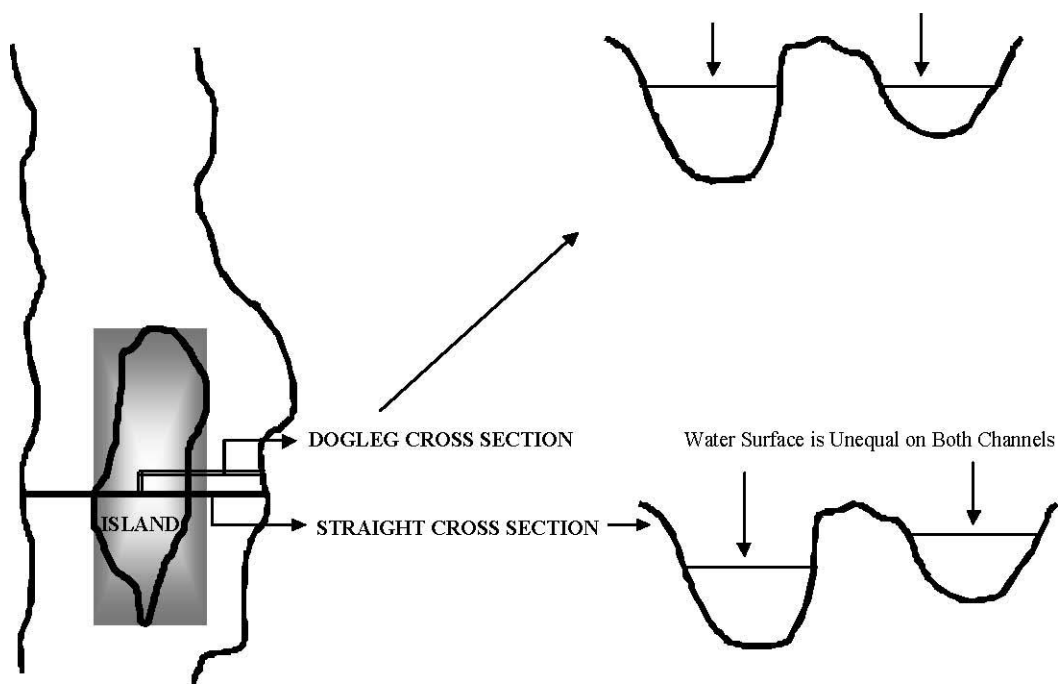


Figure 2-15. Dealing with uneven water surface elevations across an island.

downstream starting condition at each starting transect for each discharge. Then fill with **WSP** upstream (fill down in the table) over the extent of the river to which WSP is to be applied. Make these selections by clicking on the model, e.g., **WSP/STGQ** and then clicking each of the transect/discharge boxes in the table to which that model is

Water Surface Elevation Simulation

Method	Output Options	STGQ Options	MANSQ Options		
	500.000	1010.000	1300.000	1816.000	2100.000
0.000	WSP-S	94.65000	WSP-S	WSP-S	WSP-S
394.000	WSP	WSP	WSP	WSP	WSP
536.500	WSP	WSP	WSP	WSP	WSP
679.000	WSP	WSP	WSP	WSP	WSP
1028.000	WSP	WSP	WSP	WSP	WSP

to be applied. An example of a completed WSL method table is shown in Figure 2-16.

Figure 2-16. Water surface elevation method table showing entries for WSP analysis.

Next, in the **../WSP Options** tab, enter a Manning's n for each transect in the table on the left. Roughness modifiers, which are entered in the right hand table, will be discussed later. While in this tab, select the desired options using the check boxes and click

Apply. Note, all combinations of WSL simulation models are run at once by clicking the **Run** tab in **../Method**. As with STGQ and MANSQ, after the models have run, compare simulated with observed water surface elevations using the tables and graphs in **../Results**. In general, for cross sections where WSP is applied, Manning's n should be increased when the predicted WSL is low and decreased when predicted WSL is high. The WSL at the downstream transect is not changed by the WSP model. The laboratory exercises will provide you with experience with the WSP calibration process

Several key hydraulic parameters related to the computational procedure within WSP are output to ZOUTnn. Although not all of these variables are in the output for each cross section, they are usually located somewhere in the output from a WSP run. Their definitions are provided below and have been illustrated in Figure 2-4.

HF1 = Head loss computed at downstream section. HF2 = Head loss computed at upstream section. HSF = Slope (S_e) of energy grade line at section. HV1 = Velocity head ($v_1^2/2g$) computed for downstream section. HV2 = Velocity head ($v_2^2/2g$) computed for the upstream section. Total Head = Total head loss (h_f) between sections.

Remember to review the output file for error messages and inconsistencies in the data. Error messages in the form of notes or other statements may be written to the output file and not appear on the screen or cause the program to abort. Output from the WSP model is both extensive and variable depending on the particular run options that the user selects. Examination of WSP output is deferred to the laboratory exercises.

Modeling Of Velocities In PHABSIM

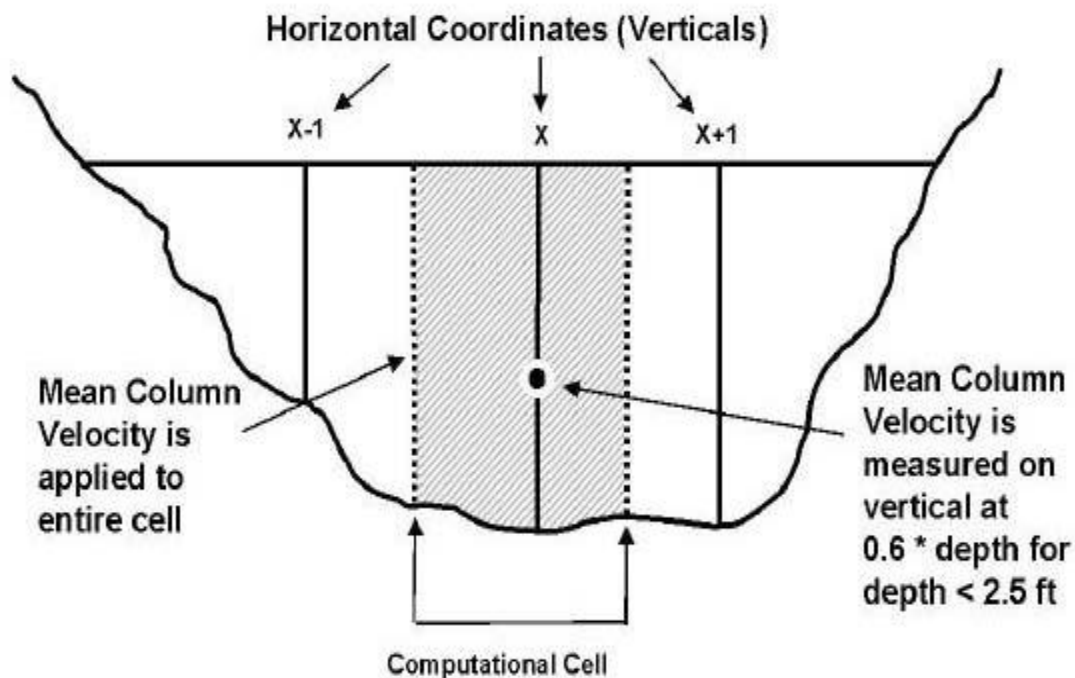
The second major step of hydraulic modeling within PHABSIM involves simulating velocity profiles at each cross section within the river. Transect based open channel flow models face a serious limitation in simulating velocity distributions across the channel. Both step-backwater and stage-discharge type models were developed and have been verified only for whole channel calculations. Thus, lacking a theoretical method of distributing velocities, PHABSIM relies on empirical means to approach this problem.

PHABSIM models velocities for individual cross sections and as such treats the cross sections independently regardless of the model employed to generate the WSLs. In most cases, only limited resources are available to do field work in any particular instream flow study; hence, a limited number of velocity profile readings are used to estimate the velocity distribution at flows for which velocities were not measured. Within PHABSIM, the VELSIM model is used for all velocity predictions. Those velocity values are subsequently used in the habitat modeling portion of PHABSIM. Figure 2-17 illustrates the relationship between a measured velocity at a cross section vertical and a computational cell as viewed by the VELSIM model.

Note that both the STGQ and VELSIM programs define a computational cell as the region one-half way between two sets of adjacent verticals (see Figure 2-17). A vertical is a measurement point specified as the X (distance from the head stake) coordinate values (see Chapter 1). All references to the computational cell are then made to the vertical. Note that this definition of a cross-sectional cell is different from that used by the habitat models. These differences are discussed in more detail under the appropriate habitat models in Chapter 5.

In PHABSIM, each computational cell in a cross section is treated separately, with its own depth, substrate, and average velocity. In the VELSIM program, there is a one-to-one correspondence between mean column velocities and the X coordinate of the vertical at which the velocity was observed or simulated. Velocities can only be provided at X coordinate values in **/Edit/Cross Sections/Coordinate Data**. PHABSIM for Windows does not limit the number of subdivisions (or cells) used to define the velocity distribution across a cross section. Obviously, the more computational cells per cross section, the more detailed the description of the velocity distribution. The VELSIM program defines a cell as the region half way between two sets of adjacent verticals as illustrated in Figure 2-17.

Figure 2-17. Measured velocity and computational cell velocity.



Calibration and Simulation of Velocities

In the following discussions, approaches to estimating the velocity distribution at a cross-section are described. The first section describes use of Manning's equation where no velocity measurements are made to calibrate the equation. The second section discusses the use of Manning's equation with measured velocities at one flow while the third section describes procedures using more than one set of measured velocities.

VELSIM with No Measured Velocities

The VELSIM program can be used to simulate velocities at a cross section although no velocities were measured. This is accomplished by rearranging Manning's equation to solve for "n" in terms of the measured discharge and individual cell attributes and substituting the depth of flow for the hydraulic radius:

$$v_i = [1.49 * S_e^{2/3} / n_i] / q_i$$

The net effect of this approach is that the magnitude of the velocity predicted at any vertical across the cross section is directly related to the depth of flow, and, therefore, the relative magnitudes of the velocity distributions will mimic the channel geometry as illustrated in Figure 2-18. Note that in VELSIM, if a user specifies a Manning's n value at a particular vertical, the VELSIM program will use that Manning's n to compute velocities when employing Manning's equation. The user should always check this type of simulation for realism. Experience has shown that under some circumstances, this approach yields satisfactory results, while in other circumstances it is not acceptable. Viewing plots, such as shown in Figure 2-18 in **/Models/Velocity/Results**, allows visual detection of unusual velocity distribution patterns. Note that the velocity profile in Figure 2-18 is proportional to depth.

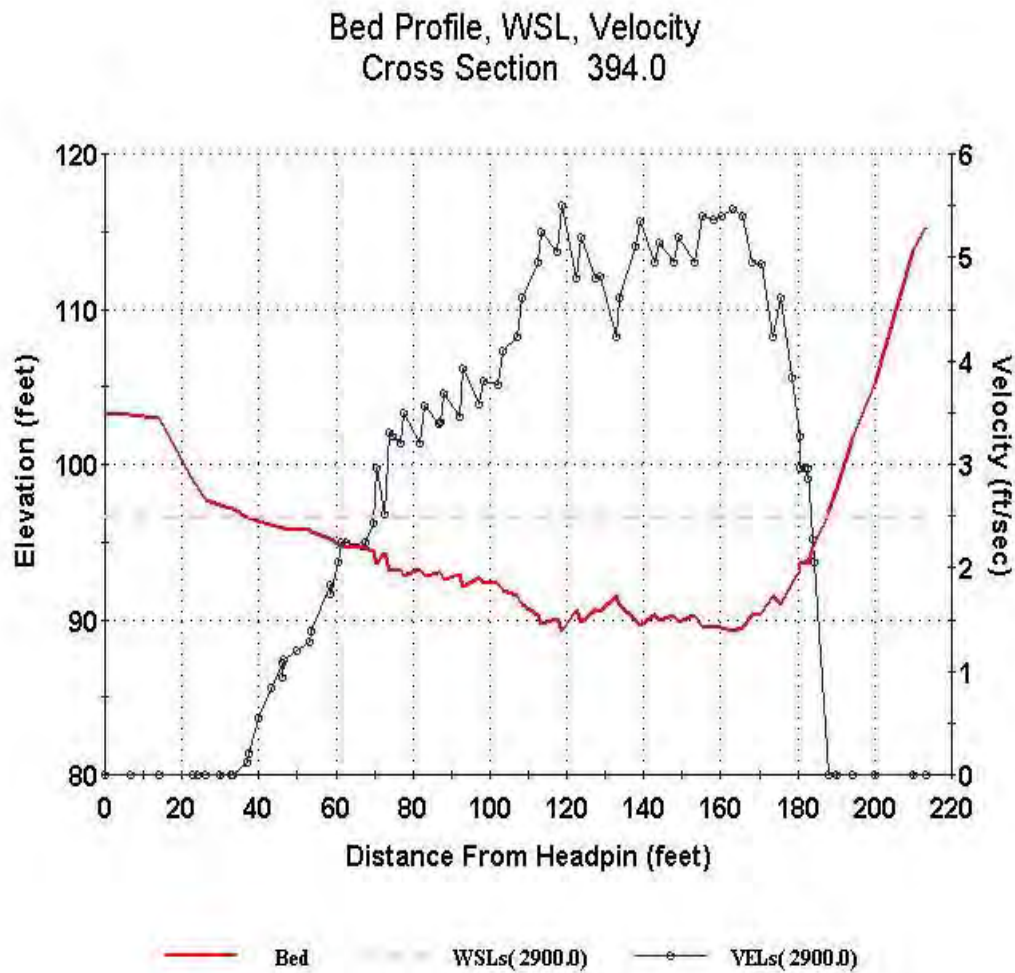


Figure 2-18. Simulated velocity distribution with no calibration data.

MESC suggests that this approach be limited to those cases where field conditions or equipment failures prevented collection of at least one velocity data set and limits of time (deadlines) or resources prevent collecting at least one velocity profile at a later time. The judgement is left up to the investigator and the particular objectives of the model application.

VELSIM with a Single Velocity Data Set

If one set of velocities is used to calibrate the VELSIM program, a different approach is taken based on an initial solution of Manning's equation to obtain an estimated Manning's n at each vertical along a cross section. This approach treats the observed velocity profile as a template for describing velocities for other discharges. Since slope, water surface, and observed velocity are given as part of the calibration data, Manning's equation can be solved for n_i at each vertical:

$$n_i = \left[1.486 * S_e^{1/2} * d_i^{1/2} \right] / v_i \quad (2-25)$$

where: n_i = estimated Manning's n value at vertical i
 S_e = energy slope for transect
 d_i = depth at vertical i
 v_i = measured velocity at vertical i

Note in this equation, that depth d_i at the vertical has been substituted for the hydraulic radius and is computed from the difference between specified water surface elevation and bed elevation at each vertical. The measured velocity (v_i) at each vertical is obtained from the input data. If a slope has not been provided (i.e., specified in **/Edit/Cross Section Data**) a default slope of 0.0025 will be used. The specific slope used is not critical to the calculation of velocities using this approach as illustrated below. Having obtained individual Manning's n values at each vertical, individual cell velocities can be computed at any alternative discharge by solving Manning's equation for velocity and using the initial Manning's n value derived from the calibration velocity set:

$$v_i = [1.486/n_i] * d_i^{2/3} * S_e^{1/2} \quad (2-26)$$

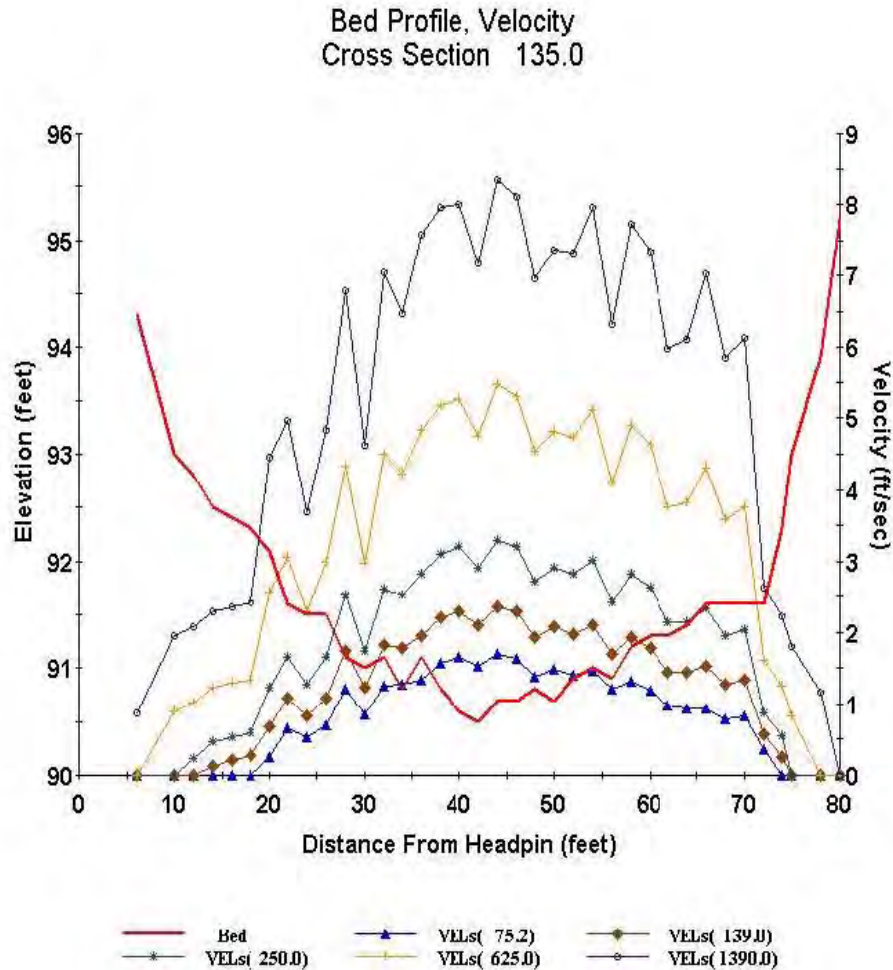
As noted above, if a user specifies a Manning's n value at a particular vertical, the VELSIM program will use that Manning's n in the computation of velocities when employing Manning's equation even though an initial calibration velocity had been provided. Figure 2-19 provides an example of a single observed velocity calibration set with the associated predicted velocities at the calibration flow. Since the best estimate of the discharge is typically used in the simulation of water surface elevations and the VELSIM maintains mass balance for the discharge, the simulated velocities at the calibration flow will not exactly “match” the observed velocities.

During simulation, if VELSIM simulates a water surface elevation at a cell for which no velocities were available for estimation of Manning's n or a Manning's n value was not supplied, the program will search for an adjacent cell to obtain an estimated or user-specified n value for use in the computation of velocities at that vertical. The user has several options for setting Manning's n in VELSIM either through a calibration velocity template or by estimation. These options are discussed in more detail at the end of this section.

VELSIM with Multiple Velocity Data

Although the investigator may have measured multiple velocity sets for use in the study, MESC recommends that the multiple velocity calibration data sets be treated as independent data sets for modeling purposes. The recommended strategy uses the highest observed velocity data set to simulate at all flows higher than the highest measured flow, the lowest observed velocity set to simulate flows lower than the lowest measured flow, and user judgement for which discharge ranges between observed velocity sets to assign each calibration velocity set. For example entirely different velocity distributions between a high flow velocity data set and a medium or low flow velocity calibration set may be found when channel geometry is very different at the associated stages. In this instance, the use of a single calibration data set over all ranges of discharges would not accurately reflect the observed velocity profiles at alternate discharges. One strategy would be to “switch” among different calibration data sets at the break in the channel geometry. The investigator would only need to determine the elevation at which this break in channel shape occurs and then determine the appropriate flow from the water surface modeling. It should also be apparent that this exercise is somewhat idealistic in that only a single cross section is shown. In practice, the user would need to consider all cross sections within the modeled reach and will therefore likely need to find a single “compromise discharge” where velocity calibration sets are changed in the model.

Figure 2-19. Velocity distribution for a single calibration discharge.



Following the strategy recommended above will result in dissimilar velocity profiles for discharges immediately above and below the break between assigned flow ranges. In some channels, this effect can be pronounced. Lacking additional velocity profile measurements, the exact transition between the calibration set velocity profiles is unknown.

An alternate scheme is provided in PHABSIM for Windows to handle this situation. That is to replace the velocity values in the ranges between observed calibration flows with a smooth transition based on the assumption that a log-log linear transition takes place. After VELSIM has been run with calibration sets assigned to each discharge of interest, the **Velocity Regression** tab is accessed. When clicked, the Run Velocity Regression button causes velocity values for each cell in the ranges between calibration discharges to be predicted using a two point regression. These values replace the values produced by running VELSIM. Note: this approach affects only the velocities in the discharge ranges between calibration discharges.

VELSIM Computational Procedures and Mass Balance In order to more fully understand the remaining computational aspects of velocity simulation within the VELSIM program, the following section describes the governing equations and process by which the VELSIM program maintains a mass balance between the requested simulation discharge and computed discharges, given its implicit computation of individual cell velocities.

The area of the cell is computed by the following equation:

$$A_i = \frac{1}{2} [(d_i + d_{(i-1)}) (X_i - X_{(i-1)})] + \frac{1}{2} [(d_{(i+1)} + d_i) (X_{(i+1)} - X_i)] \quad (2-27)$$

22

where: A_i = area of cell i

X_i = horizontal distance along the transect to point i

d_i = depth at vertical i

The “trial” discharge computed for a requested simulated discharge at the transect is then determined by using the velocity predictions for each computational cell derived from the velocity simulation method selected. These values are used to calculate cell discharges which are summed for all cells across the transect:

$$Q = \sum_{i=1}^{n_{\text{cell}}} A_i v_i \quad (2-28)$$

This apparent or trial discharge is not necessarily the same as the discharge requested in the simulation. Reference to Figure 2-15 shows the relationship between discharge and roughness and should indicate that a particular Manning’s n value derived from a velocity calibration set at a single discharge will not be the “correct” Manning’s n value at higher or lower discharges. This is the same basic concept that led to the use of RMODs in the calibration of the WSP program. An index of the difference between the requested simulation discharge and computed discharge derived from the velocity simulations is called the Velocity Adjustment Factor (VAF) and is computed by the following equation:

$$\text{VAF} = \frac{Q_{\text{requested for simulation}}}{Q_{\text{calculated from velocity simulations}}} \quad (2-29)$$

This ratio is then used to adjust individual cell velocities, v_i , which also adjusts the computational cell discharges. This adjustment proceeds until the calculated discharge for the cross section equals the requested or simulated discharge. The adjustment of the individual simulated discharges is accomplished with the VAF by adjusting the individual computational cell velocities by the following equation:

$$V_{\text{new}} = V_{\text{initial}} * \text{VAF} \quad (2-30)$$

The use of the VAF in the VELSIM program represents an empirical approach to approximate the role of the RMODs in the WSP program. The relationship shown in Figure 2-15 indicates that at simulated flows lower than the velocity calibration flows, the Manning’s n value derived from the velocity calibration flow will be too low. Since the roughness (i.e., Manning’s n) values used to estimate the velocities are too low, the estimated velocities at each vertical will be too high (see Manning’s equation). This results in a computed trial discharge for the cross section that is greater than the requested simulation discharge and the resulting VAF would be less than 1.0 (see Equation 2-30). Conversely, at simulated discharges greater than the velocity calibration flow, the estimated Manning’s n values will be high and the resulting individual computed cell velocities will be low. This results in a computed trial discharge that is less than the requested simulation discharge and the VAF will be greater than 1.0. This process suggests that in most cases the relationship between discharge and VAF should be approximately an

inverse of the relationship shown in Figure 2-15 and resemble the example illustrated in Figure 2-20. Although this general pattern is typical of most cross sections, there are occasions where the VAF versus discharge relationship will not and should not follow this generalized pattern such as when lateral bank vegetation increases the composite roughness at intermediate discharges.

In Figure 2-20, there are two ranges of discharges for which the VAF plot ascends in what appears to be different patterns. The apparent break in the VAF plot at about 250 cms is due to using different calibration sets to produce the velocity template used for velocity simulation. Within the range of discharges for which a particular set of calibration velocity measurements were used to develop the Manning’s n template, an ascending VAF relationship indicates the expected outcome of velocity simulation. It should also be noted that the VAF at the calibration flow will not always be equal to 1.0. For example, during the modeling process, the user may have selected the best estimate of discharge for a group of cross sections where the measured variability in computed discharges may have been 15–20%. For any cross section that has a computed discharge based on a set of calibration velocities that is not exactly the same as the best estimate of the discharge, the VAF will deviate from 1.0. The magnitude of the deviation will depend on the magnitude of the deviation between the best estimate of the discharge and the discharge computed using the calibration velocity set.

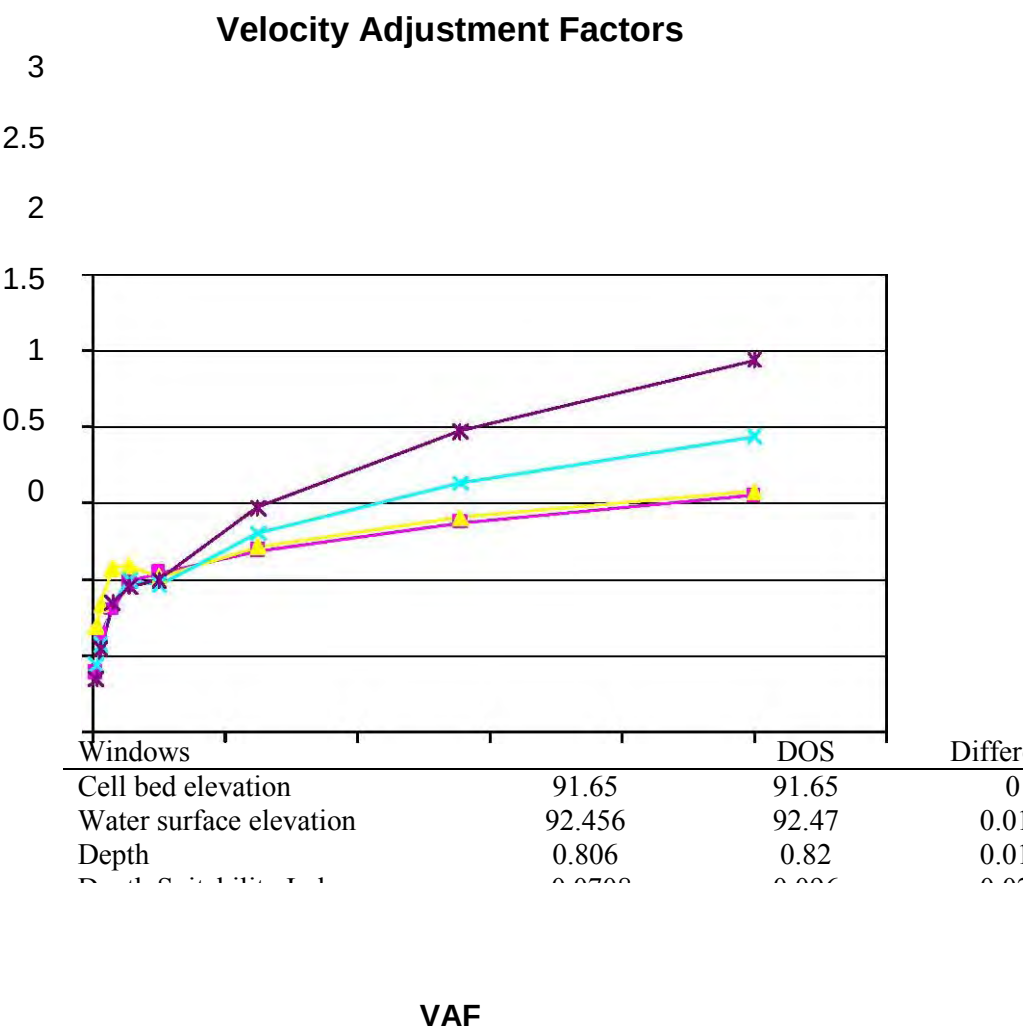


Figure 2-20. Velocity adjustment factors.



It is also reasonable to expect that the VAF relationships for sections with similar cross section geometry will be similar in their functional relationships and the variation between VAF versus discharge relationships will be directly related to the degree of variability in the cross section geometry. As a final note on VAFs, there is no rational basis for judging the “validity” or quality of the hydraulic simulations based strictly on the magnitude of the range in computed VAF values. That is, there is no specific set of envelope values that the VAF should absolutely lie within. It is only an index of the relative change in discharge from the calibration discharge used at the calibration velocity versus the simulated discharge which follows the relationship between roughness and discharge shown in Figure 2-15. The shape of the VAF versus discharge plot is a better indicator of model performance than the VAF magnitude. When a monotonically increasing VAF relation is not obtained, it is not necessarily an indication of model failure. Rather, it simply is an indication that the model calibration and simulation steps should be reviewed. Some channels exhibit non-standard VAF plots even when the models are performing well.

Significance of Initial Slopes and Manning’s n Values in VELSIM

Note that slope does not appear in the four equations above which describe the computation of velocity and mass balance in the VELSIM program. Also, the slope used in the initial calculation of Manning’s n will not influence the final calculation of the velocity. The slope is important only in being able to compare individual Manning’s n values at cross section verticals from one cross section to another or from one stream to another. The selection of Manning’s n values to add to a data set to control velocity simulations is easier however, if a reasonable estimate of slope is used to calculate roughness from the calibration velocities. The Manning’s n value at this point within the VELSIM program really represents a velocity distribution factor. The user should not be too surprised if individual cell Manning’s n values do not fall within the expected ranges reported in hydraulic roughness tables for cross sections containing a particular substrate characteristic. Handbook values are estimated for whole channel conditions (often for high flow conditions as well) and not for a particular vertical within a cross section.

The role of Manning’s n in VELSIM is important since it functions strictly as a velocity distribution factor and can have an impact on results of the habitat models. In general, since velocities are not measured at previously dry verticals, n values will have to be estimated by the program or supplied (i.e., estimated) by the user. However, the Manning’s n values for velocity distribution are derived in one way or another. Whether they are calculated from observed velocities, estimated for the cell by the VELSIM program when no velocity data is supplied, or supplied by the user, that Manning’s n values are used to calculate the cell velocity for all simulated discharges. This is primary importance when simulating higher flows because, when simulating down from a measured velocity calibration set, the program will have Manning’s n values computed from known velocities at all verticals.

Simulation of higher discharges can, however, lead to problems at the edge of the stream where fringe cells may contain very small cross sectional areas at the calibration discharge. When Manning’s n_i values for dry cells are not supplied by the user, the program will search adjacent cells for a given or calculated n_i or will assume a value of 0.06 if none are found. However, the VELSIM program will occasionally predict unrealistically high velocities on the stream margin (e.g., 20 feet/second!) due to the combination of Manning’s n estimation and application of the VAF to achieve mass balance. Since these areas may be very important to certain life stages of aquatic species being studied, the user should carefully examine the velocity simulation results for these “artifacts” of the computational process during VELSIM calibration. Use the **Cross Section** plot button in **Models/Velocity/Results** to view simulated velocity profiles and the tabular velocity results to determine which cells need to have n values supplied to improve erroneous edge velocities. In these instances or where other factors may warrant, the value of n_i for dry cells (or wet cells) should be supplied by the user in the **/Edit/Cross Section/Coordinate Data** tab. This is covered in more detail in Laboratory 6 on velocity calibration and simulation.

Nose Velocities

Much attention has been given to the debate on mean column versus nose velocities (also called focal point velocities) in PHABSIM applications for prediction of available habitat. The HABTAE model offers the user a variety of modeling choices for the computation of nose velocities either based on the distribution of bed material particle sizes, regression equations based on mean and nose velocity measurements, or by empirical relationships based on the 1/7 power law, to name a few. The application of these techniques however, is limited to those situations where nose velocity habitat suitability curves are available and sufficient field data has been collected to support use of these hydraulic modeling options. Additional descriptions of nose velocity calculations and options are included later in this manual under the HABTAE model program and will not be discussed further here.

Control of VELSIM Calibration and Simulation Options

Much of the utility of the VELSIM program lies in the ability of the user to provide very specific control over all aspects of the computational procedures. The user should review available options for the VELSIM program listed in Table 2-6. This review often results in some confusion for the user to decide which combination(s) of options should be selected to achieve the desired results. This problem can be overcome by breaking up available options into several discrete conceptual parts that are provided below.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Table 2-6. Options in the VELSIM program.

Table 2-6. Concluded.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Velocity Adjustment Factor and Mass Balance

Use Velocity Adjustment Factor: {tc /l4 “Use Velocity Adjustment Factor } This option in essence will allow the user to ignore application of the VAF to achieve a mass balance within the VELSIM model. If this option is not checked, mass balance determined from application of the VAF will be ignored. In most cases, this box should be checked so mass balance will be enforced and the VAF applied.

Controlling Roughness: Several options are available to the user to control the way in which the VELSIM program will use roughness.

Calculate N for Wet Cells {tc /l4 “Calculate N for wet cells}: This option allows the user to control the way in which the VELSIM program will calculate roughness or how it uses the roughness if supplied (i.e., Manning’s n).

If not checked: This option instructs the VELSIM program to use roughness for a cell if it is input in the coordinate data. If n is zero, the VELSIM program will compute the Manning’s n value if a velocity is available, use an adjacent value if available, or use the default value of 0.06.

If checked: This option will result in VELSIM calculating the Manning’s n value for cells that are wet, using Manning’s n if supplied for dry cells, or estimating Manning’s n for dry cells if the Manning’s n value in the cell is 0.

Limit Manning’s n {tc /l4 “Limit Manning’s n}: This option allows the user to specify the maximum and/or minimum value of the roughness computed with the Manning’s equation during the simulation of velocities. The maximum and/or minimum value is specified in the input cells provided in the /Models/Velocity/Options Window.

If not checked: This will result in no limit on value of the estimated Manning's n value.

If checked: This will impose the limit for the maximum and/or minimum as specified on the NMAX data line. IF the estimated Manning's n value exceeds these limits, it will be set to the appropriate limit for use in all simulations of velocities in that cell.

Variable roughness coefficient {tc /14 "Variable Roughness Coefficient}: This option allows the user to adjust the roughness in a cell as a function of depth in a cell. This option can help reduce the negative impacts arising from too high a roughness at edges of the stream calculated at lower discharges that would be expected to become less rough as flow (i.e., depth) increases. NOTE: Leave the Velocity Adjustment Factor box blank or the results will be irrational when using this option.

If not checked: The program will not calculate variable roughness.

If checked: The program will adjust roughness as a function of discharge and requires the user to specify a B exponent in the box provided in the **/Models/Velocity/Options** Window.

The general equation for changing roughness as a function of depth is:

$$N = n_c * (d/d_c)^B \quad (2-31)$$

where: n = depth adjusted Manning's n value for the cell

n_c = calibration Manning's n value for the cell

d = depth of the cell at the current discharge

d_c = depth of cell at the calibration discharge

B = an empirical coefficient in the range from -2.04 to 0.0

The estimation of "B" for use in variable roughness has received little discussion in the literature and only those with an advanced familiarity with hydraulic modeling should consider the use of this option.

Evaluating Quality of the Hydraulic Modeling

In the preceding sections, the basic theory and steps to achieve the calibration and simulation of both water surface elevations and velocities were presented. This section address some of the more fundamental issues in evaluating the quality of the hydraulic modeling effort. Evaluation of water surface elevations is discussed first followed by a discussion of velocities.

Evaluation of Water Surface Modeling

Predicted Versus Observed Water Surface Elevations at the Calibration Flows

Perhaps the most fundamental diagnostic of the quality of hydraulic modeling of the water surface elevations is how close are the predicted and observed water surface elevations at the calibration flows. This leads to the question of how close is close enough? Unfortunately, no readily available answer can be dogmatically stated. In general, the user should attempt to match the observed and predicted water surface elevations with no error, but this represents a case not readily achieved in applied hydraulic modeling. The user will often be faced with trading accuracy at one set of measured calibration flows to achieve a better fit at over the full range of calibration flows. For example, the user may be able to replicate the observed water surface elevation longitudinal profile using WSP at the lowest calibration flow but no RMOD can be found to achieve an exact match for the high calibration water surface profile. An alternative re-calibration of the WSP model to the high flow may result in replication of the longitudinal profile, but again, no RMOD can be found which adequately replicates the low flow profile. In this instance, the user is likely to use the WSP model which is most accurate nearest to the flow range in which the

instream flow questions are likely to be the most contested. As a general guideline, in most applications predicted versus observed water surface calibration errors which are on the order of 0.01–

0.02 feet can be achieved. It is not uncommon; however, that a single or a few cross sections may deviate more (e.g., 0.03–0.05 feet or more) depending on the characteristics of the channel geometry, gradient, left versus right bank differences in water surface elevations (remember that only a single value is used for all models). Potentially, a hydraulic control may have been missed during field collection or a hydraulic control is migrating within the channel over the range of discharges collected. It is possible however, to evaluate the application or performance of each of the models and demonstrate that the “best” calibration/model combination achievable with the available data is actually used in the study. It may not be possible to overcome poor model performance with the collection of new or additional data. In such a situation, the degree of uncertainty must be clearly reported and kept in the forefront during the evaluation of study results.

Longitudinal Profiles of the Water Surface Elevations

A second measure of the quality of the modeling for water surface elevations is the examination of the longitudinal profiles of the water surface elevations over the entire range of simulated discharges. That is, where the cross sections are all measured to a common survey datum, the longitudinal WSL plots can be examined to determine whether or not water “flows uphill”. Such a situation would indicate that the range of simulated discharges should be restricted for the application of that particular WSL model to flow ranges over which the results are consistent (i.e., water flows downhill). In many applications, one or more models (e.g., STGQ and MANSQ) may perform well within the range of the measured calibration discharges but only work well at some reduced range of extrapolated discharges. At these higher discharges of interest, the only WSP model may be adequate and the user can elect to WSP to simulate over all ranges of flows or for only the higher flows where the other models would not be appropriate.

Valid Ranges of Simulated Discharges

Some individuals have used the absolute range of simulated discharge, that is, how much higher than the highest calibration flow and how much lower than the lowest calibration flow, as a measure of the quality of the simulations. In earlier PHABSIM manuals, ranges of “acceptable” simulations have been reported as 0.4 to 2.5 times the measured discharges. Under some circumstances a range of 0.2 to 1.5 has also been reported. The user should note that, from a functional, algorithmic, or mathematical perspective, **none** of the models (i.e., STGQ, MANSQ, or WSP) are inherently restricted to any range of acceptable simulation limits from a hydraulic perspective. In some applications, very restrictive ranges are required due to channel configuration, model performance and adequacy of the available data, while in others, extremely wide ranges (i.e., 0.1 to 10) are justified by model performance. What constitutes a valid range of simulated discharges in the absence of poor model performance (i.e., “water flowing uphill”, large calibration errors, etc.) is a matter of professional judgement. At present, no rigorous peer reviewed evaluation of WSL simulation limits using any of the hydraulic models for specific types of channels and site specific field conditions has been undertaken. The user is cautioned that a reasoned limit to the reliable range of simulations should be based on model performance given the available data rather than an arbitrary “rule of thumb”.

Evaluation of Velocity Modeling

Perhaps one of the most difficult aspects of evaluating hydraulic simulations involves the evaluation of the velocities. When no calibration velocities are available, it is a matter of professional judgement as to the utility of the velocity distributions based on depth as long as the obvious “errors” such as high velocity artifacts at the stream margins have been corrected. Another potential indication of problems in the simulations would be extremely “odd” VAF relationships which have no rational basis in physical characteristics at a cross section.

In those instances in which a single velocity set has been used in the simulations, it is a matter of professional judgement as to the quality of the simulations, assuming that any erroneous velocity errors have been accounted for. However, if during a review of the channel characteristics for the cross sections it is determined that gross changes in channel geometry occur at some “threshold” water surface elevation (i.e., discharge), then the velocity simulations should be carefully examined to determine if the distribution across the change in channel geometry makes rational sense. This situation often arises where only a single velocity set was collected at a low flow or alternatively at only the high flow and a large “floodplain” type geometry exists. It is unlikely (but not impossible) that a standard application of the single calibration velocity set will reflect the velocity magnitudes and distributions across such a radical change in channel geometry. Modification of the velocity simulations using professional judgement is the only real option if the collection of an additional velocity calibration set(s) cannot be accomplished under the constraints of the project.

In those instances where multiple velocity sets have been collected, the user can easily check the validity of the velocity simulations by comparing the predicted velocities to one or more of the other calibration velocity sets. In the event that the predicted versus observed velocity profiles are not within an acceptable range, then one or more of the other calibration velocity sets should be used for the appropriate range of discharge. Channel geometry changes in this situation can often provide guidance to the analyst for the water surface elevation and hence discharge ranges, that a particular velocity calibration set might be most appropriate. Again, any VAF functional relationship which deviates from the “expected” relationship should have a physical justification based on site-specific characteristics.

Chapter 3. Habitat Suitability Criteria

Objectives

This chapter briefly introduces the basic nomenclature and common types of habitat suitability criteria used in PHABSIM. For a more detailed discussion of this subject, the reader is referred to Bovee et al. (1998).

Laboratories

The associated exercise for this material is Laboratory 7. That exercise reviews the HSC numbering convention and the mechanics of managing HSC curve sets within the PHABSIM for Windows environment.

Introduction

Successful implementation of PHABSIM requires the acquisition of accurate and realistic habitat suitability criteria for the target organism(s) being evaluated. Perhaps more important than accuracy and realism, however, is buy-in from the stakeholders. Because the output from PHABSIM is extremely sensitive to even subtle differences in habitat suitability criteria, establishing the credibility of the criteria can be of utmost importance. Sometimes, establishing credibility requires a scientifically designed study to define a species' habitat characteristics. At other times, the habitat suitability is the result of expert opinion and negotiation. A key concept for PHABSIM analysts is that there is no universal best way to develop habitat suitability criteria. There are many ways to develop criteria, and alternative approaches to using them in PHABSIM, all of which have certain advantages and disadvantages. In simplest terms, criteria can be distinguished by their format and the type of information used to develop them.

Format

Use of the term format refers to the way that the habitat suitability criteria (HSC) are presented. In practical terms, there are only two viable formats for use in PHABSIM: binary or univariate curve (Figure 3-1). The binary format, shown as a shaded rectangle, brackets a range of a continuous variable (e.g., depth, velocity, distance from shore). Binary criteria act as simple on-off switches: the suitability index for a variable is 1.0 if it falls within the bracket and is 0.0 otherwise. Different ranges can be used to represent distinct categories of microhabitat quality for the target species. For example, a relatively narrow range can define habitat conditions preferred or selected by a life stage or a more all-encompassing range can define conditions the organism will use, but not seek out. Binary criteria can even be used to describe conditions avoided by the target species. In this case, the output from PHABSIM would quantify unsuitable, rather than suitable, microhabitat. **Note:** Binary criteria as used in PHABSIM are really specialized forms of the univariate curve, because vertical lines (e.g., two y-values for a single value of x) are illegal. Separating the x-values at the edges of the rectangle by a razor-thin difference closely approximates binary relations. For example, in Figure 3-1, the minimum usable depth for the binary criteria is 0.65 m. The coordinates entered into PHABSIM would be (0.649, 0.00) and (0.65, 1.00).

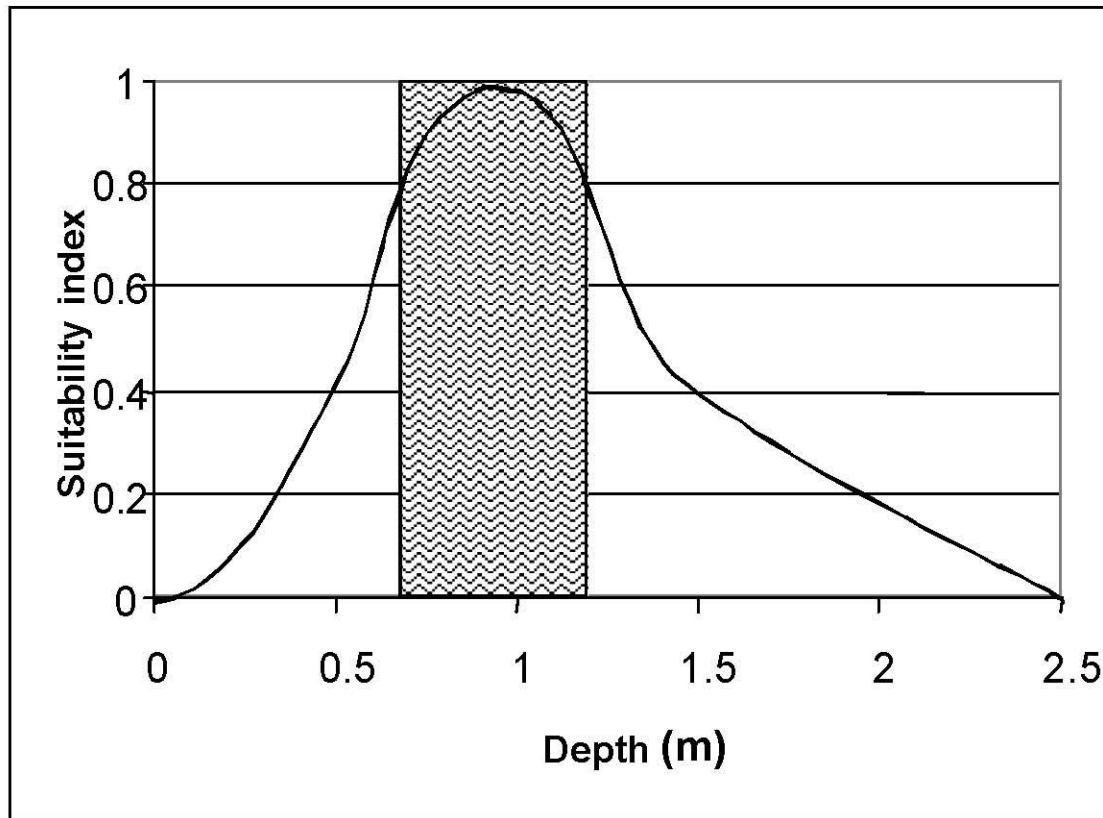


Figure 3-1. Comparison of binary and univariate curve formats for habitat suitability criteria.

Waters (1976) proposed the use of the univariate curve (Figure 3-1) as a more robust alternative than binary criteria for expressing habitat suitability. Since then, this has become the most familiar criteria format associated with PHABSIM. The tails of the curve are designed to encompass the entire suitable range of a continuous variable, but the narrow peak of the curve represents the optimum. Intuitively, the appeal of the univariate curve is that it is all-inclusive. Credit can be granted for conditions that are of intermediate habitat value, between optimal and barely useful. As popular as it is, however, the univariate curve has its detractors. Morhardt and Mesick (1988) summarized the concerns about univariate curves and the physical habitat generated by PHABSIM as follows:

1. When calculating the composite suitability index, PHABSIM treats variables independently so potentially significant interactions between variables are ignored.
2. Weighted usable area, which results from the use of univariate curves, is an index and cannot be measured directly.
3. Different estimates of weighted usable area can be obtained by using different methods of aggregating the composite suitability index.

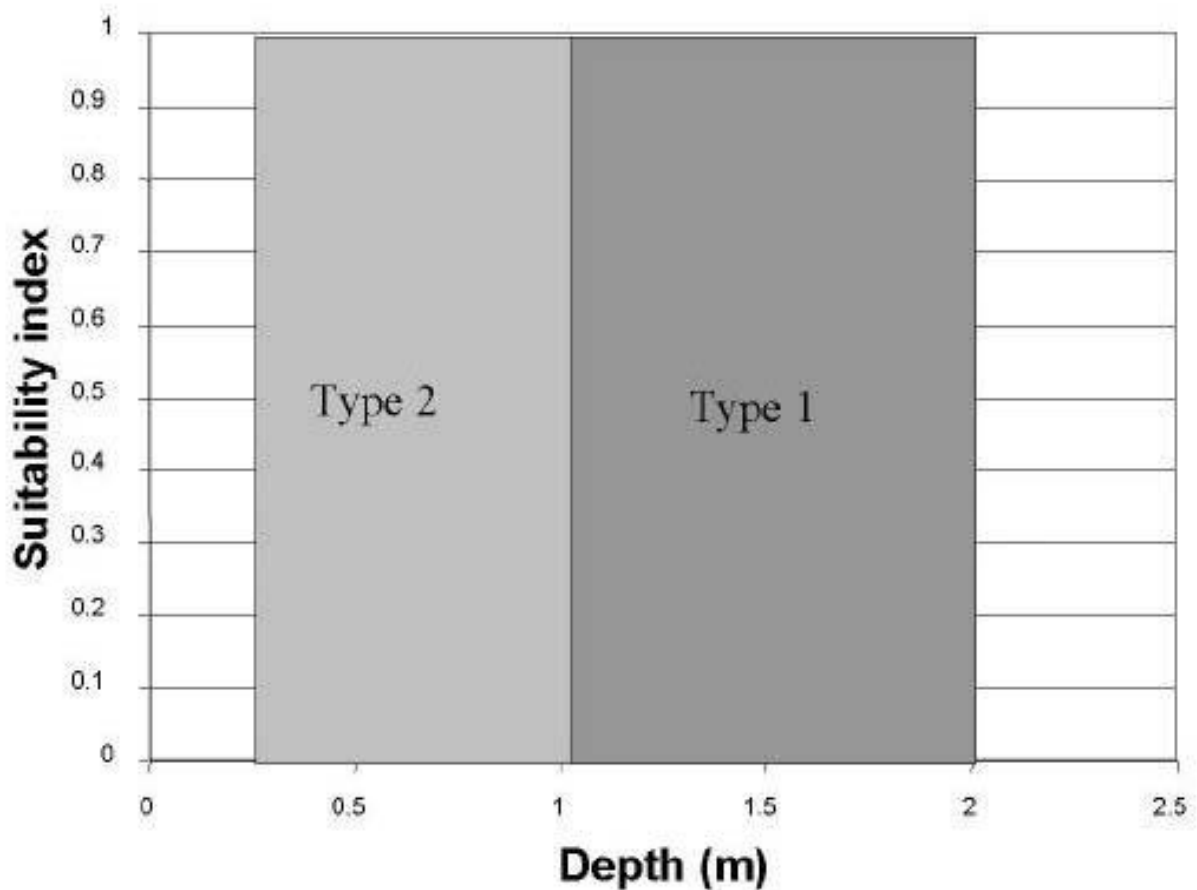
Weighted usable area combines elements of habitat quantity and habitat quality. A large area of low-quality habitat can produce the same weighted usable area as a small amount of high-quality habitat. **Conditional criteria** are used to depict interactions among habitat variables that are known to be biologically important (Bovee 1986). An example of a biologically significant interaction is the use of deep water as a form of overhead cover by some species of fish. The fish will occupy shallow water areas if overhead cover is present, but will only use deeper areas where cover is absent. This phenomenon can be represented through the use of two sets of criteria: one where overhead cover is present and one where it is absent (Figure 3-2). Presence or absence of cover can be designated in the HSC by clever usage of the channel index (e.g., 1 = no cover and 2 = cover in the cell). Wherever a channel index of 1 is encountered, usable habitat is tallied only for cells with adequate depth according to the deep-water criteria. Where the channel index is 2, usable habitat is accounted using the

shallow-water criteria. In the PHABSIM software, this is accomplished by using two sets of HSC, one for deep water and the other for shallow water. The habitat areas for the two simulations are then summed to determine the total habitat, with and without cover. Similarly, surface turbulence can be modeled as a form of overhead cover by using the Froude number (a ratio of potential to kinetic energy) instead of velocity to compute the composite suitability. In this case, cells without overhead cover would be unsuitable unless the Froude number was high enough to indicate surface turbulence. As currently programmed, specialized habitats such as Froude number dependence require review of the computational details in the project.ZOUTn file to extract and sum habitat for the appropriate cells.

Figure 3-2. Categorical depth criteria. Type 1 applies to cells that do not contain overhead cover. Type 2 applies to cells with overhead cover.

HSC Categories

The term category refers to the type of information and data treatment used to generate the criteria. Criteria that are derived from personal experience and professional opinion, or from negotiated definitions are defined as **category I**. These criteria can be developed relatively quickly and at minimal cost, compared to more data-intensive approaches. Because the criteria are negotiable, obtaining consensus about the criteria may also forestall conflict over their subsequent use in PHABSIM. The principal drawback to category I criteria is that they are based on opinions instead of data. Credibility problems can arise when the criteria are presented to groups that were not involved in the original development process.



Category II criteria are based on frequency distributions of microhabitat attributes measured at locations used by the target species. These criteria are known as **utilization or habitat use functions** because they represent the conditions that were being occupied by the target species when the observations were made. This approach for criteria development dates back to the conceptual precursor of PHABSIM, a planimetric mapping method developed by the Washington Department of Fisheries (Collings, et al., 1972). The **Washington method** was designed to measure the amount of spawning area available to Pacific salmon at various streamflows. Because the methodology was oriented to spawning, criteria development consisted primarily of finding salmon redds and measuring depths and velocities at various locations around them. After a sufficient number of redds were measured, binary criteria were developed to encompass a specified range of the observations.

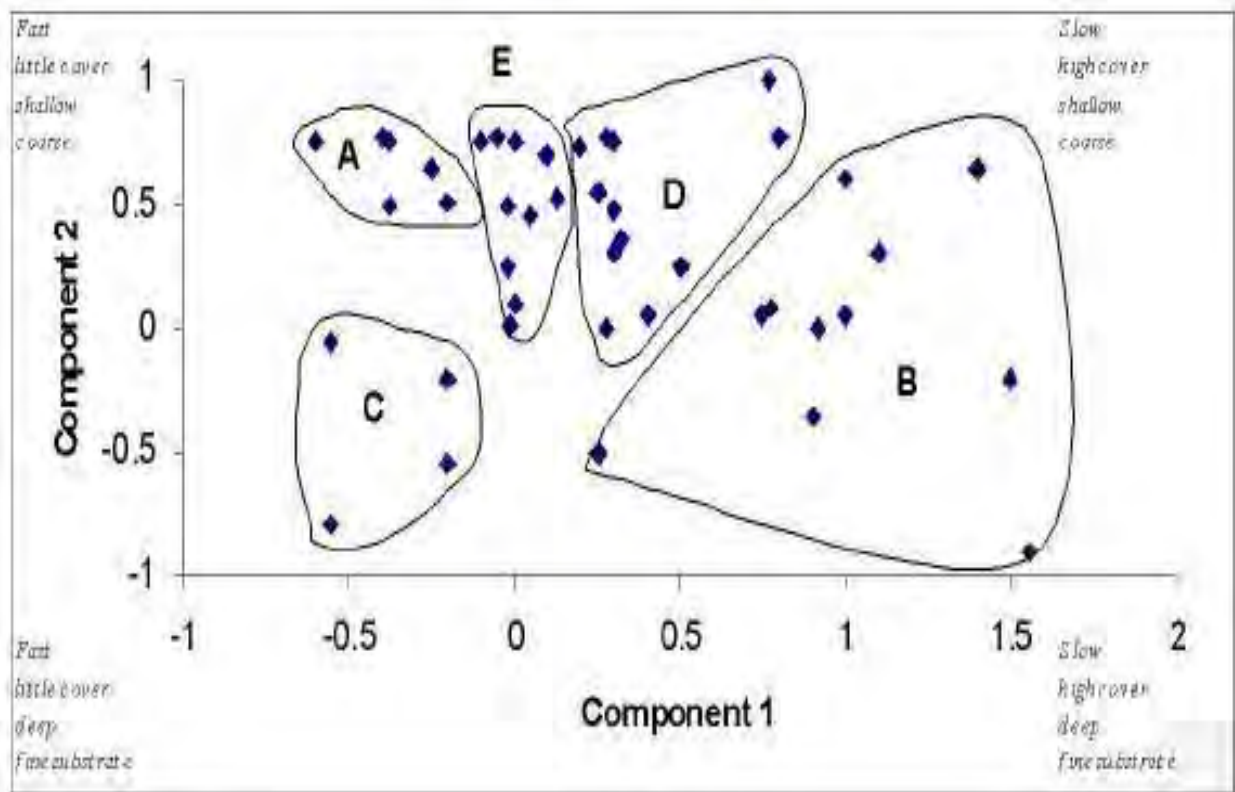
During the formative years of PHABSIM, the same basic approach for developing habitat suitability criteria was expanded to other species and life stages. One popular sampling method was to use a team of divers to intensively search numerous small reaches of stream to find locations occupied by the target species. At the end of each search, the depth, velocity, cover type, substrate (and other pertinent data) were measured at each occupied location. After measurements had been taken at 100 to 200 locations, the investigator either defined a binary range for the criteria or fit the data to a univariate curve.

Another approach to developing category II criteria is exemplified in the work of Knight, et al. (1991). They used a pre-positioned electrofishing grid to sample randomly selected locations throughout their study area. To take a sample, a grid was positioned at a pre-determined (random) location and left undisturbed for at least 15 minutes to allow fish to resume their normal activities. At the end of the waiting period, fish were collected by electrifying the frame for approximately 20–30 seconds. Immediately after activating the power supply, a seine was placed downstream of the frame so that stunned fish were swept into it. With the power active, one person kicked through the frame to dislodge benthic species. Fish captured at each location were preserved for later identification in the laboratory. Habitat attributes (e.g., depth, substrate type, cover type, and velocity) were measured at the four corners of the frame for each sample, and averaged.

A multivariate analysis of variance (MANOVA) was used to detect differences in habitat composition between samples that contained a particular species and those that did not. Principal components analysis (PCA) was used to illustrate the position of each fish species in habitat space (Figure 3-3). These analyses were used to identify habitat attributes that consistently corresponded to high abundance and diversity of fish species. Variations of this method have also been described by Felley and Hill (1983), Bain, et al. (1988), Scheidegger and Bain, (1995), and Bowen (1996).

The benefit of category II criteria is that they are based on data, not on someone's opinion. However, error can be introduced to these criteria through a **bias of environmental availability**. Manly, et al., (1993) describe this bias in the following way. Even though a resource item is highly favored by a species, it will not be used much if the resource is hard to find. Conversely, less favored resource items will be used in larger proportion if they are the only ones available. In the context of microhabitat utilization, this means that individuals will be forced to use sub-optimal conditions if optimal conditions are unavailable. By observing only the conditions used the most often in a given stream, an investigator could confuse optimal microhabitat with conditions that were merely tolerable.

Figure 3-3. Mean species locations in habitat space defined by principal components analysis of pooled data from seven streams in the Alabama River basin. Irregular circles encompass species with similar habitat use (e.g., Group C includes saddleback darter [*Percina vigil*], Alabama hog sucker [*Hypentelium etowanum*], black redhorse [*Moxostoma duquesnei*], and highfin carpsucker [*Carpiodes velifer*]. From Knight et al. (1991).



Category III criteria are designed to reduce the bias associated with environmental availability. These criteria are also referred to as **electivity or preference functions**. Resource selection refers to the utilization of resources disproportionate to their availability (Manly et al. 1993). For example, suppose that 10% of the stream mesohabitats occur as riffles, but 90% of the target species are found in riffles. Such disproportionate use is interpreted as an active selection on the part of the target organism.

A wide variety of mathematical indexes have been developed to indicate selection, and in some cases, avoidance of various resource units. The index of electivity usually involves a comparison of the proportion of the resource used with the proportion available or unused. [Available includes both used and unused proportions of the resource.] The most familiar index of selection, at least with respect to habitat suitability criteria, has been the forage ratio:

$$E = \frac{U}{A} - 1$$

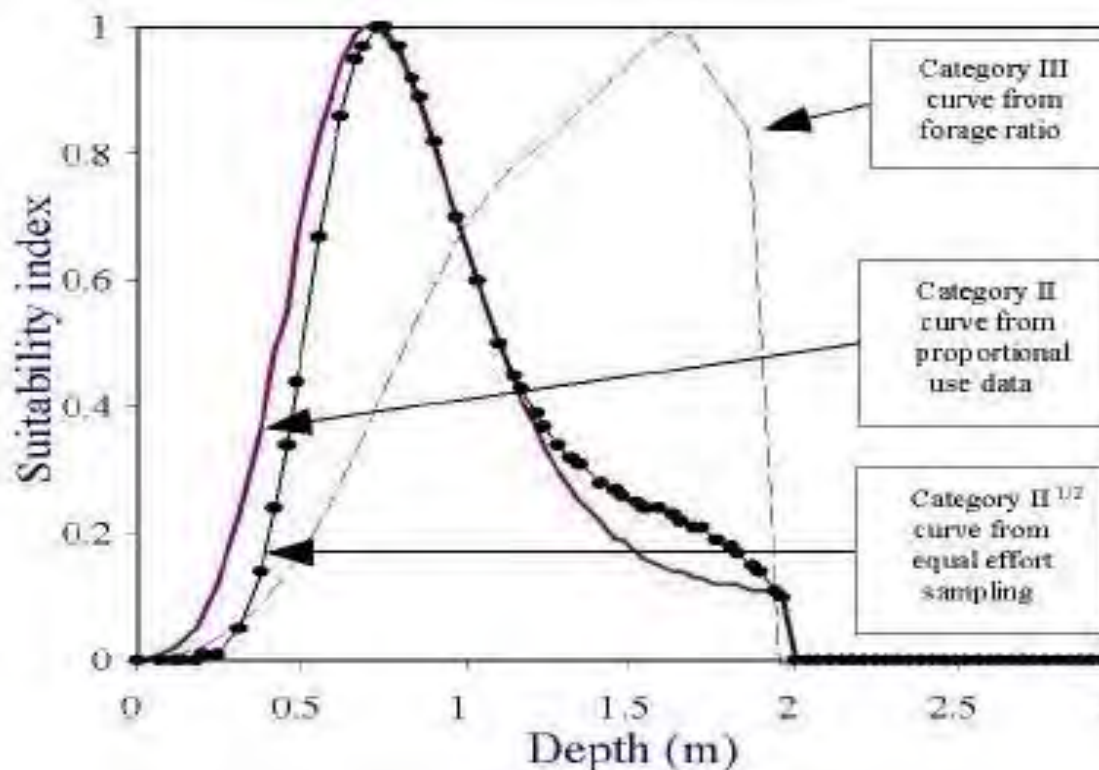
where E is an index of electivity, U is the proportion of used habitat units of category I (for example, depths between 1.0 and 1.5 m), and A is the proportion of habitat units of category I available in the sample. The use of the forage ratio was promoted as the preferred approach for developing habitat suitability criteria during the mid-1980s (Bovee, 1986). Since then, the method has fallen from favor (Bovee et al., 1998) because the forage ratio can result in an over-correction of the criteria (Figure 3-4). An alternative approach originates from the definition of preference given by Johnson (1980), who described preference as the likelihood that a resource will be selected if offered on an equal basis with others. Conceptually, the way this definition applies to habitat suitability criteria would be if it were possible to develop criteria in a stream with a perfectly uniform distribution of an infinite variety of microhabitat conditions. According to Johnson's definition, one could determine habitat preference simply by measuring use, because all microhabitat conditions would be equally available. Obviously, streams fitting this description are few and far between (as in non-existent). However, it may be possible to approximate this condition by altering the sampling design when collecting habitat utilization data. Following this

strategy, each mesohabitat type would be sampled equally, regardless of its relative abundance in the stream. The premise underlying the concept of **equal-effort sampling** is to equalize the availability of microhabitat conditions within the sampled sub-population, to the extent possible.

Criteria Verification

Although not a required element for running PHABSIM, criteria verification is always a good idea. Remember that in IFIM, the currency for negotiations is total habitat and alternatives are evaluated by comparison with a baseline. What this means is that habitat does not necessarily have to have a demonstrated biological connection, as long as the currency is meaningful to the stakeholders and decision-makers. For negotiations of low to medium levels of conflict, criteria can be verified simply by obtaining their acceptance among the stakeholders. When it becomes impossible to obtain consensus among the stakeholders, however, it may be necessary to conduct an empirical verification test.

Figure 3-4. Comparison of depth suitability curves for active adult brown trout derived from proportional use data (category II), equal effort sampling (category II $\frac{1}{2}$), and forage ratio correction for availability (category III).



If PHABSIM sites are already established, one method to verify the criteria is to measure the standing crop in each site, calculate the habitat availability at the same discharge, and relate the two statistically. This procedure has two advantages. First, a significant correlation is unlikely if the criteria are incorrect, so the chances of committing a Type I error (accepting criteria when they should be rejected) are fairly remote. Second, a significant correlation lends credence to the idea that microhabitat is biologically meaningful. The disadvantages of this procedure are that the correlation may not be significant for reasons other than inaccurate criteria and the results are sensitive to the timing of the surveys. One often overlooked reason for poor correlation is the error associated with the estimate of standing crop. Before getting too excited about a lack of significant correlation, it is a good idea to examine the confidence intervals for the population estimates at each site. You may find that differences in standing crop cannot be quantified reliably enough to perform this type of test. A related problem occurs when trying to validate criteria for sport fish, because places that have good fish habitat also attract fishermen. Sometimes sites with the best and most abundant microhabitat will have the smallest standing crop, simply because all the good habitat may be “fished out.”

Thomas and Bovee (1993) presented a more robust statistical test for criteria verification. This test can be performed without having to establish a PHABSIM site and is less influenced by fishing pressure than the previous method. Also, the results of the Thomas-Bovee method are not dependent on accurate estimates of standing crop. The primary disadvantages of this method are that it requires relatively unbiased habitat use and non-use data. The results are meaningful at the individual level, but not necessarily at the population level. In other words, the criteria may be transferable, in the sense that they describe fish behavior, but there is no guarantee that habitat estimates from the criteria are related to fish numbers.

Under the Thomas-Bovee method, habitat use is determined either by complete census or sampling and a random sample of **unused** habitats is taken. Criteria to be tested are converted from univariate curve to binary format, with the optimum range for a variable defined as having a composite suitability index greater than 0.85. Usable microhabitat is defined as having a composite suitability value between 0.2 and 0.85. Suitable microhabitat is defined as the full range of conditions in which the target organism is observed. Unsuitable microhabitat is defined as all values outside the suitable range. From the criteria, each used and unused location is classified as being optimal or usable, and suitable or unsuitable.

Then, each sampled location is cross-classified (e.g., occupied-optimal, unoccupied-usable) into a 2 x 2 contingency table (Table 3-1). The null hypotheses H_{01} (optimal locations will be occupied in the same proportion as usable locations) and H_{02} (suitable locations will be occupied in the same proportion as unsuitable locations) are tested using a one-sided chi-square test (Conover 1980). The test statistic T is given as:

$$T = \frac{N(ad - bc)}{\sqrt{(a+b)(c+d)(a+c)(b+d)}} \sqrt{N(3-2)}$$

$$(a+b)(c+d)(a+c)(b+d)$$

where N is the total number of measured locations, a is the number of occupied optimal locations, b is the number of occupied usable locations, c is the number of unoccupied optimal locations, and d is the number of unoccupied usable locations. Suitable locations are substituted for optimal locations and unsuitable locations for usable to test classifications of suitable and unsuitable microhabitat.

For a set of criteria to be considered transferable, both null hypotheses should be rejected at the 0.05 level of significance. [Note: The critical value of T at this significance level is 1.6449, and is obtained from the normal distribution table, not from the chi-square distribution. See Conover (1980) for a full discussion.]

Discussion Items

- In PHABSIM, it is equally important to describe habitat variables used over a broad range as to find narrow habitat preferences. Sometimes, these criteria appear as thresholds, above or below which there is little selection. The empirical frequency distribution of used microhabitat may be artificially narrow, either because the range of available conditions was narrow or because of the method used to fit the criteria to the data. Such artificially narrow criteria can make PHABSIM output unrealistically sensitive to changes in discharge. If this phenomenon is suspected, it should be brought to the attention of the stakeholder group. Modifying a data-based curve on the basis of professional judgement is acceptable, if not encouraged.
- Category I criteria are as valid in an application of IFIM as data-based criteria, if they are supported by a consensus of opinion among the stakeholders. Criteria developed by a committee are often somewhat broader than those based on data, because the ranges of the criteria are often negotiated. In this respect, category I criteria rarely exhibit artificial narrowing, but can be too all-inclusive. If the criteria are too broad, PHABSIM output may be relatively insensitive to changes in discharge.
- The principal components analysis approach presented by Knight et al. (1991) differs most dramatically from the other methods we discussed. A unique advantage of this method is that it can be used to define habitat use guilds and critical habitat types. This allows the analyst to concentrate on only a few key habitat types, rather than analyzing habitat for multiple species and life stages. Furthermore, potential biological connections between the habitat type and the biology of the stream can be quantified through the statistical analysis.
- It may come as a surprise to newcomers to PHABSIM, but it is just as valid to develop habitat suitability criteria for a mesohabitat type as it is for a species. For example, suppose that riffles are considered to be a critical mesohabitat type. A riffle could be defined with binary criteria, as having a depth range between 1 and 75 cm, velocities between 45 and 90 cm/sec, and a gravel/cobble substrate (or other definitions as negotiated among stakeholders). PHABSIM could then be used to determine how much area met those criteria over the range of simulated discharges.
- There is no unbiased way of collecting habitat use data. Every kind of sampling gear or observation technique has some sort of limitation that can result in biased data. For example, even with good visibility, divers are more apt to spot fish in shallow water than in very deep pools. They are also more likely to find active fish than those at rest, because the human eye is attracted to movement. As another example, electrofishing is less effective in deep water, and for safety reasons may be restricted to depths less than 1 m. When evaluating criteria, consider the limitations of the methods used to obtain the data in the context of the source stream from which the data were collected. If you believe that the criteria are unduly biased, refer to the first observation.
- One of the assumptions related to the estimation of resource selection functions is that the variables, which actually influence selection, have been correctly identified and measured. Perhaps the most common misconception about PHABSIM is that the only microhabitat variables that can be used are depth, mean column velocity, and substrate. In fact, PHABSIM can accept a wide range of variables, provided that they are related to the hydraulics or the structural characteristics of the stream. Examples of alternative microhabitat variables include: nose velocity, adjacent velocity (important for feeding stations), cover type, distance to cover, distance from shore, proximity to another habitat type, sheer stress, Froude number, depth-velocity products (important for recreational activities), and depth as a form of cover. Additionally, it is possible to use PHABSIM in conjunction with commercially available spreadsheets to derive alternative habitat indexes, such as habitat diversity. Be aware that

you are not limited to the “default” variables. With a little imagination, it is usually possible to tweak PHABSIM to include microhabitat attributes known to be important to the target species.

Organization of Habitat Suitability Criteria in PHABSIM

HSC number in PHABSIM for Windows arranges habitat Suitability Criteria (HSC). The HSC numbering convention consists of a four digit species identifier followed by a two digit life stage identifier. Each species and each life stage is also identified by a text description. A typical HSC curve would be identified as follows:

100102 Brown Trout Fry

The species identifier 1001 is associated with Brown Trout and the life stage identifier 02 is associated with fry. The PHABSIM software organizes HSC selection options and the format of the results from habitat calculations based on this number and text convention. Thus, it is important that each species/life stage have both a unique numerical and text identifier.

One may have different kinds of habitat suitability criteria for the same species in a project. That is, one may have a day time HSC series denoted by 1001 for Brown trout and a night time series denoted by 1101. Following this example, an HSC numerical identifier of 110102 would represent Brown Trout Fry habitat suitability at night. No strict correspondence between numerical identifier and life stage is enforced. Thus a curve number 110126 could be used for nocturnal Brown Trout Fry and the software would process it properly.

Problems can arise, however, if one attempts to assign different text identifiers to the same numerical species identifier and if either the species or life stage text identifiers are left blank. The PHABSIM for Windows interface is looking for consistent association of species text and numerical identifiers across all life stages and for unique life stage names associated with the numerical life stage identifier.

The HSC are entered in PHABSIM as x,y pairs of data to describe univariate relations for the suitability of depth, velocity, channel index, and temperature. Each variable must have an initial ordinate of 0 and a final ordinate of 100. Often, these curves begin with 0,0 and end with 100,0. A typical set of HSC is illustrated in Table 3-2.

Table 3-2. Brown trout adult HSC ID number and criteria coordinates.

Brown Trout – Adult HSC ID Number: 100101 Velocity SI Depth SI Channel Index SI						
0.0	0.40	0.0	0.00	0.0	1.00	
0.5	1.00	1.0	1.00	1.0	1.00	
2.5	0.00	100.0	1.00	9.0	1.00	
100.0	0.00	100.0	1.00			

From this format, it can be seen that exact binary criteria cannot be represented. Rather, a close approximation is used. For example if binary velocity criteria for adult brook trout consisted of a range from 0.5 to 2.0 ft per second that had a suitability of 1.0 and all other suitability values were 0.0, the representation in PHABSIM might be as follows (Table 3-3).

Table 3-3. Representation of binary brook trout adult velocity criteria coordinates.

Velocity SI
0.00 0.00
0.49 0.00
0.5 1.00
2.0 1.00
2.01 0.0
100.0 0.00

Accessing Habitat Suitability Criteria in PHABSIM for Windows

HSC are entered and managed in the **\Edit\Suitability Curves** window. This window has menu items for **File**, **Edit** and **Curve**. The **File** menu allows for importing existing HSC criteria from text files (PHABSIM Version 2. Curve files) or from other PHABSIM for Windows projects. Thus it is possible to use an existing curve set in a new study by simply importing the old HSC data. Similarly, the import feature makes it possible to create a project with the purpose of maintaining a library of HSC curves and select the desired HSC for each study as needed.

The **Edit** menu allows the user to interactively add new curves, copy curves to new curve ID numbers and species/life stage names and to delete individual curves. One may add a new curve by supplying ID numbers, species/life stage names and the respective HSC coordinates for depth, velocity and channel index. To change from velocity to depth, channel index or temperature, one clicks the appropriate radio button in the **Curve Type** box to the upper right. Click the desired radio button (i.e. depth) and enter the HSC values in the table. Be sure to fill in all HSC tables before exiting. Or, for example, new channel index criteria can be assigned to an existing curve by making a copy of the curve, supplying new identifying information and then entering new coordinate data for the channel index values. The delete function deletes the curve currently displayed in the window.

The **Curve** menu allows selection of the curve displayed in the window by ID number or by moving backward and forward in the list of HSC contained in the project. It also provides for displaying graphs of individual curves or of the four HSC in each curve set.

One can display the individual HSC as they are being entered when adding curves under the **Edit** menu by clicking the **Graph** button located at the lower right of the window. By sizing or dragging the graph window and the Suitability Curve window one can view data as it is being entered and catch data entry errors as they occur. For more complicated HSC graphs, using the zoom feature may enhance viewing of particular portions of the curve. The graph automatically updates when a different curve is selected. As you click the different radio buttons for depth, velocity, etc. the graph changes to that variable.

Summary of Chapter 3

This chapter covered a brief outline of the numerous considerations needed when using HSC in a PHABSIM analysis. Because HSC are often the source of the greatest variability in PHABSIM study

results, it is of utmost importance that consensus as to the form and numerical values of the criteria be achieved among stakeholders **prior** to beginning the actual PHABSIM work. The processes for developing habitat suitability criteria are outside the scope of the PHABSIM for Windows software so the discussion in this chapter is provided as a very brief introduction to the topic. Readers are referred to the various references for more detailed coverage of this topic.

The chapter concludes with a description of the HSC data management capabilities of PHABSIM for windows. In any study, the HSC need to be entered into the PHABSIM project before proceeding to the habitat analysis process. Habitat analysis in its numerous forms is described in Chapter 4.

Chapter 4. Habitat Modeling

Objectives

The objectives of this chapter are to introduce the basic concepts of habitat modeling used within PHABSIM followed by a presentation of the specific computational processes important to the successful application of each habitat model within PHABSIM.

Laboratories

The associated laboratory exercises for this chapter will introduce the specifics of the two average parameter models AVDEPTH and AVPERM in Laboratory 8, general habitat modeling (HABTAE) in Laboratory 9, conditional velocity modeling in Laboratory 10, and finally lateral migration in Laboratory 11.

Introduction

At this point in a PHABSIM analysis, the needed hydraulic model(s) has/have been applied to determine characteristics of the stream in terms of depth and velocity as a function of discharge for the full range of discharges to be considered for the study. In the habitat modeling process, this information is integrated with habitat suitability criteria (HSC) to produce a measure of available physical habitat as a function of discharge.

The general theory behind the habitat modeling programs within PHABSIM is based on the assumption that aquatic species will react to changes in the hydraulic environment. These changes are simulated for each cell in a defined stream reach. The stream reach simulation takes the form of a multi-dimensional matrix of the calculated surface areas of a stream having different combinations of hydraulic parameters (i.e., depth, velocity, and channel index) as illustrated in Figure 4-1. The depth and velocity for each cell is the average of the simulated depth and velocity values obtained from the hydraulic simulation phase of PHABSIM. Depth and velocity attributes vary with simulated changes in discharge, causing changes in the amount and quality of available habitat. The end product of the habitat modeling is a description of habitat area as a function of discharge as illustrated in Figure 1-4 reproduced here as Figure 4-2 for ease of reference.

This habitat-discharge relationship is the basis of further analysis from which fishery and recreation management decisions are developed in IFIM. By linking the habitat-discharge relationship with flow time series data, a habitat time series can also be developed as described in Chapter 5. This information can assist in identifying critical time periods for a given life stage, limiting habitat availability for each life stage (i.e., physical carrying capacity), and limiting habitat availability for different species. When combined with a habitat time series, the habitat discharge relation is particularly useful in evaluating potential changes in species composition, because of the associated changes in the hydraulic characteristics of the stream reach as a function of discharge.

Figure 4-1. Matrix of habitat cell attributes in a PHABSIM study site.

Corresponding habitat value representing a composite of depth velocity and channel index for each cell

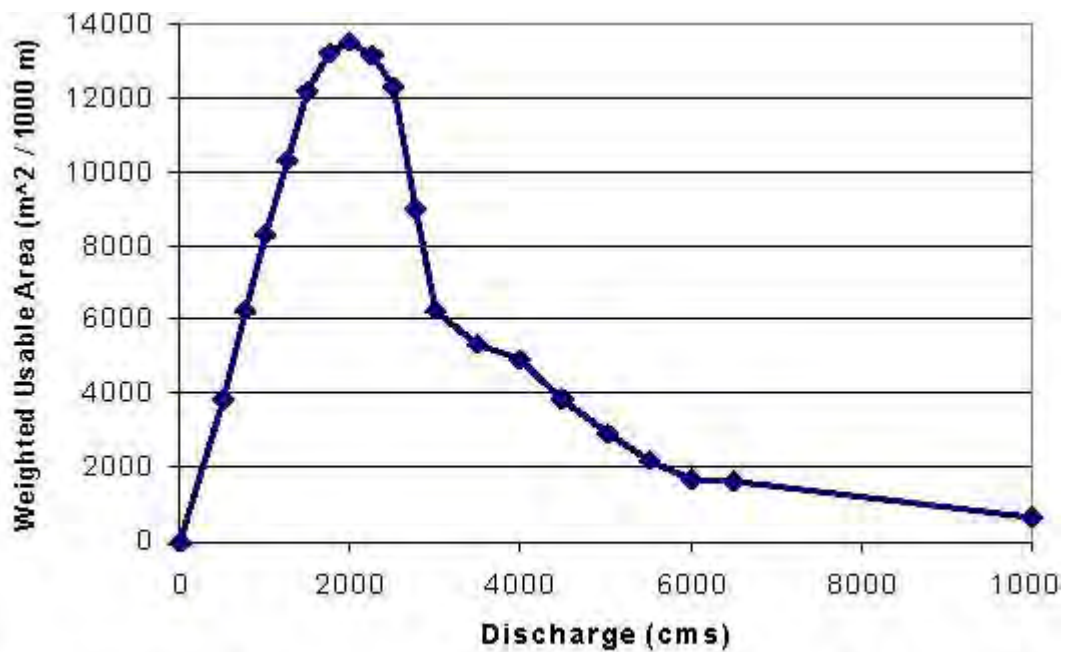
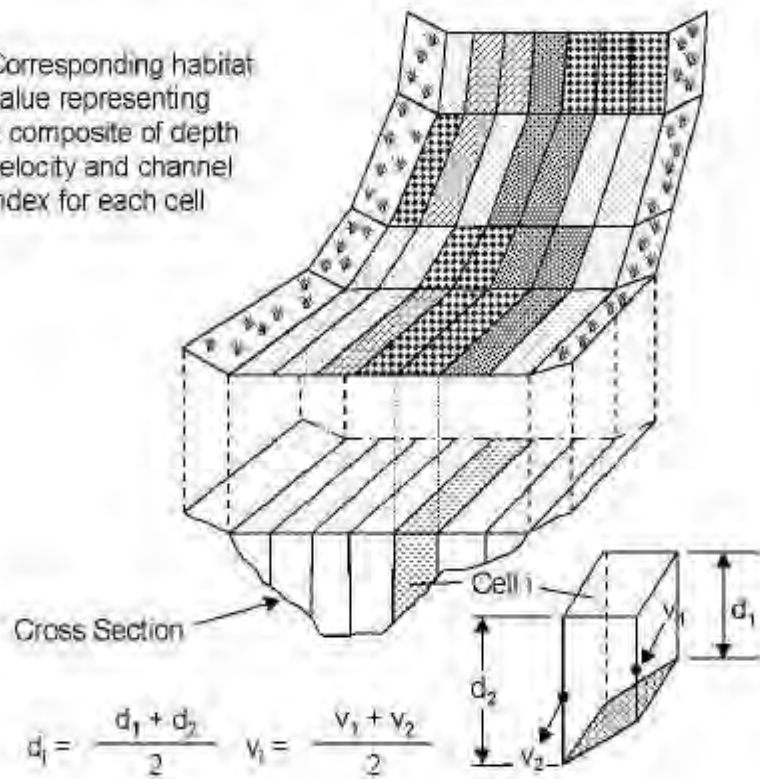


Figure 4-2. Habitat-flow relation for one species/life stage derived from a PHAB SIM analysis.

This chapter presents material on how the habitat models view a stream based on the information passed from the hydraulic simulation programs; how the habitat models use the reach lengths, upstream weighting factors, and their linkage to habitat mapping or representative reaches to derive area (or volumes); and the generalized conceptual and analytical approaches used in the habitat models to integrate the hydraulic and suitability curve data to produce the basic metrics of habitat quantity and quality. The chapter concludes with a detailed description of each of the specific habitat models within PHABSIM and the available computational options within each habitat model.

The following section provides a discussion of several ways in which the output from the habitat models can be interpreted and how model results fit within the broader context of ecological assessment of alternate flow regimes.

Habitat Model Computational Cells

Figure 4-1 shows a generalized representation of a river segment for a series of transects that define a matrix of habitat cells with their associated attributes of depth, velocity and channel index (i.e., substrate and cover). These habitat cells represent the basic computational cells used by the various habitat programs to derive relevant indices of available habitat. This information is obtained from the hydraulic simulation models, as described in Chapter 2. In PHABSIM for Windows, all habitat models view a habitat computational cell the same way. In previous versions of PHABSIM there were two different cell definitions. As noted in Chapter 1, the change to one type of habitat cell definition may affect the computed habitat values when certain conditional habitat options are selected.

As noted above, all habitat programs now represent the habitat computational cells as bounded by the points where verticals were measured in the field. The hydraulic models define a cell as one-half the distance to the next vertical in each direction. Thus, the hydraulic models simulate depths and velocities (shown as d_1 , d_2 , v_1 and v_2 in Figure 4-1) at the verticals used in the habitat models.

Deriving Habitat Computational Cell Areas and Volumes

During the discussion of the project data (see Chapter 2), the distance from the previous cross section and upstream weighting factors supplied in **/Edit/Cross Sections** were described. The distance from the previous cross section (or reach length) and the upstream weighting factors (or reach length weighting factors) are used by the habitat models to assign a length to the habitat computational cells in the longitudinal direction for each cross section and, thereby, impart a surface area to each cell. Since the bed elevations are also known, several habitat model options can also be used to derive individual cell volumes and stream bed areas for use in calculating available habitat. A clear understanding of the relationship between the reach lengths and reach length weighting factors is necessary for proper use and interpretation of the habitat modeling results as illustrated in Figure 4-2 and discussed below.

Representative Reaches

Figure 4-3 illustrates a stream segment in which three cross sections have been used to characterize this “representative” reach. Each cross section was placed in a unique habitat feature as indicated. In Figure 4-3, the reach lengths measured between the left and right bank head pins at each cross section have been indicated, starting at the downstream cross section and moving in an upstream direction. The reach length at the downstream-most cross section by definition is zero (0) since there is no previous cross section and this is the value entered in the **/Edit/Cross Sections/Cross Section Data** field for length for the first cross section.

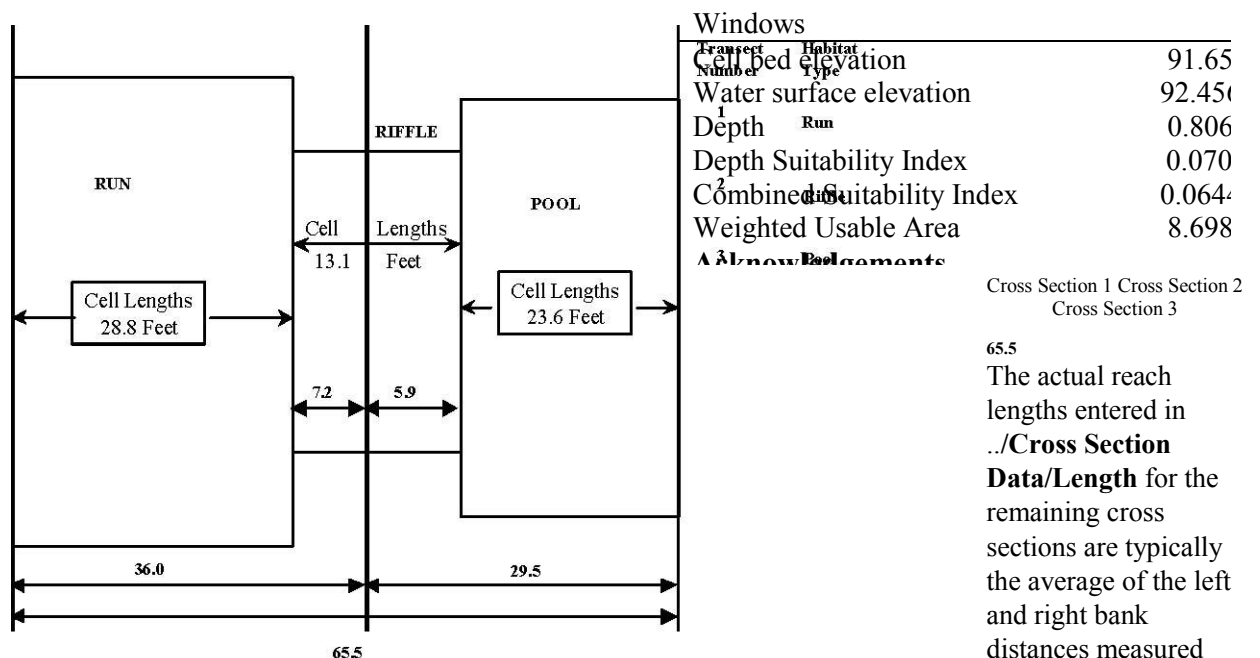


Figure 4-3. Derivation of reach length weighting factors.

rectangles without "bends". Use of the **Left** and **Right Bank Weighting Factors** can accommodate the actual left and right bank distances to preserve the spatial orientation or "bends" is discussed later in this chapter.

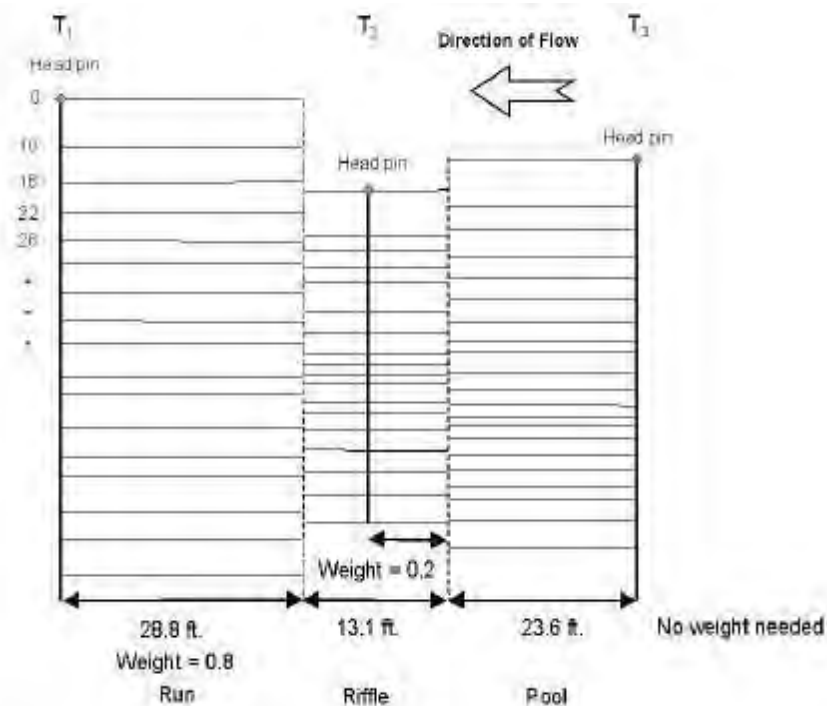
The **Reach Length Weighting Factors** (upstream weighting factors) are the values used in the habitat models in conjunction with the reach lengths to derive the longitudinal distance represented by cells at each cross section. In the example illustrated in Figure 4-3 in which a representative reach approach has been undertaken, the investigator would define during field data collection how far in the upstream direction, the attributes represented at the current cross section (i.e., habitat feature) extend toward the next upstream cross section. This upstream weighting factor is entered in the **/Edit/Cross Sections/Cross Section Data** field for **Upstream WF** for that cross section. For example, the investigator may have decided that the run habitat type represented by the downstream most cross section extends approximately 80% of the average distance upstream to the second cross section located in the riffle. In a similar manner, the investigator may have also decided that the second cross section located in the riffle only represents characteristics approximately 20% of the distance moving upstream to the transect located in the pool. This would result in an upstream weighting factor for the downstream-most cross section having a value of 0.80 and a value of 0.20 at cross section two. Any value between 0.0 and 1.0 may be supplied at the last cross section located in the pool since there is no upstream cross section and the area upstream of the last cross section will not be considered when calculating habitat. The resulting cell lengths for the downstream cross section would therefore be derived by distance calculated from the product of the Reach Length Weighting Factor at Cross Section One (i.e., 0.80) times the Reach Length Distance at Cross Section Two (i.e., 36.0) or $(0.80 \times 36.0) = 28.8$ feet in Figure 4-3. This implicitly defines a longitudinal distance for cells at the second cross section of 7.2 feet in the downstream direction (i.e., $36.0 - 28.8$). The remaining longitudinal distance in the upstream direction at cross section two would be computed by taking the upstream weighting factor at cross section two (i.e., 0.20) and multiplying it by the reach length value entered on the XSEC data line at cross section three (i.e., 29.5 feet) to derive an upstream longitudinal distance of 5.9 feet. The **total** longitudinal distance (e.g. length) of all cells at cross section two is then derived by the addition of these two parts and would yield 13.1 feet for this example. The length of all cells at cross section three is derived by subtracting the upstream distance at cross section two (i.e., 5.9 feet) from the reach length distance entered for cross section three. In

this example it would be 29.5–5.9 or 23.6 feet.

Note that the last cross section does not have a contribution of a longitudinal distance in the upstream direction and that the first cross section does not have a length contribution in the downstream direction. Figure 4-4 illustrates the final "internal" representation of the habitat computational cells as defined in the previous example.

Figure 4-4. Habitat computational cells represented within the habitat models.

From this approach to cross sections weights, if the upstream weighting factor at cross section two had been specified as 1.0, then cross section three would have no length in the habitat model and, therefore, not contribute to the computation of available habitat. Similarly, if the upstream weighting factor at cross section one had been set to 1.0 and



the upstream weighting factor at cross section two had been set to 0.0, then cross section two would have effectively been eliminated from use in the habitat models. The use of reach lengths and, in particular, upstream weighting factors to "eliminate" a cross section or cross sections such as hydraulic controls used for hydraulic simulation purposes only, is easy to accomplish using such an approach.

Changing upstream weighting factors to reflect relative contributions of specific types of habitat and impacts on the overall contribution to habitat availability can also be facilitated using these concepts. The next section illustrates use of the reach lengths and upstream weighting factors to represent stream segments in which specific types of habitats were sampled and which represent the proportions that these specific habitat features occur within a longer stream.

Habitat Mapping and the Idealized River Reach Approach

Table 4-1. Example of transect weighting based on reach length and upstream weights to duplicate percentage of habitat types within a study reach.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

For illustration purposes, assume that a river segment has been habitat mapped (see Bovee, et al., 1998 and Morhardt, et al., 1983) over some suitable length and it was determined that four distinct habitat types were recognizable and were found to occur in the following proportions based on measured longitudinal distances:

20% pools 60% runs 10% riffles 10% glides

The investigator randomly selected two locales of each habitat type and subsequently collected data from each set of four habitat types and now has successfully modeled the hydraulic conditions at 8 cross sections (i.e., 4 habitat types X 2 cross sections / habitat type). The investigator would now like to conduct habitat modeling at all 8 cross sections such that the weight given the individual cross sections reflects their proportional contribution as measured by the habitat mapping indicated above. Therefore, it is desired that both cross sections in pools total 20%, both cross sections in runs total 60%, both cross sections in riffles will total 10%, and both cross sections in glides total 10%. Because a stratified random sampling procedure was used, all 8 cross sections were collected independently and were spread out over 20 miles of river so the representative reach approach described in the previous section is not an option. The following example is one of several possible approaches which combine reach lengths and upstream weighting factors to weight the relative contribution of each cross section in order to produce the desired habitat mapping weighting in the calculated WUA results.

First, assume that all the transects represent 100% of an idealized river reach or alternatively, consider the idealized river as being 100 feet long. The basic strategy, is to specify reach lengths and upstream weighting factors for each /Edit/Cross Sections/Cross Section Data field such that the combination of distance and weights produce the following results: (1) both of the pool transects have a combined total habitat computational cell length of 20 feet (or 20%), (2) runs represent a total of 60 feet, (3) riffles represent 10 feet, and (4) glides represent 10 feet. This approach requires using the STGQ and/or MANSQ programs because these programs treat each cross section independently. Note, WSP can be used to simulate a pool transect provided that the control transect governing the pool is “weighted out” as described above and the pool transect reach length fits into the overall distance weighting scheme. Assuming the investigator has decided to enter the data grouped by habitat type and in the order of the habitats listed above, we only need to specify the appropriate reach lengths and upstream weighting factors at each cross section, which could be accomplished as indicated in Table 4-1.

Note that the “solution” for this example could have been handled in any number of different ways to yield the same basic results. The habitat models will produce an index of habitat availability (i.e., WUA) in units of square feet per 1000 feet of stream and therefore using total distances of 1000 or 10,000 for the total idealized reach will only “scale” the WUA magnitudes by factors of ten. This is different than that obtained from using a representative reach since, in that approach, the actual reach lengths are spatially dependent. If the relative combinations between reach length and weighting factors result in approximately the same relative contributions of specific habitat types sampled, then the functional relationship between habitat and discharge will be nearly the same using either approach.

The “end product” of these efforts within the hydraulic simulations using STGQ or MANSQ is the generation of an

array of stream cells representing each cross section as illustrated in Figure 4-1 at each simulated discharge. This “array” of cells and corresponding attributes of depth, velocity, and channel index is passed to the habitat programs and, as indicated above, represent the basic habitat computational cells. The use of these attributes and associated area, volume, or bed area in each cell in conjunction with the HSC curve coordinate data to generate an aggregated index of available habitat is discussed in the next section.

Integrating Habitat Suitability Criteria Curves and Computational Cell Attributes

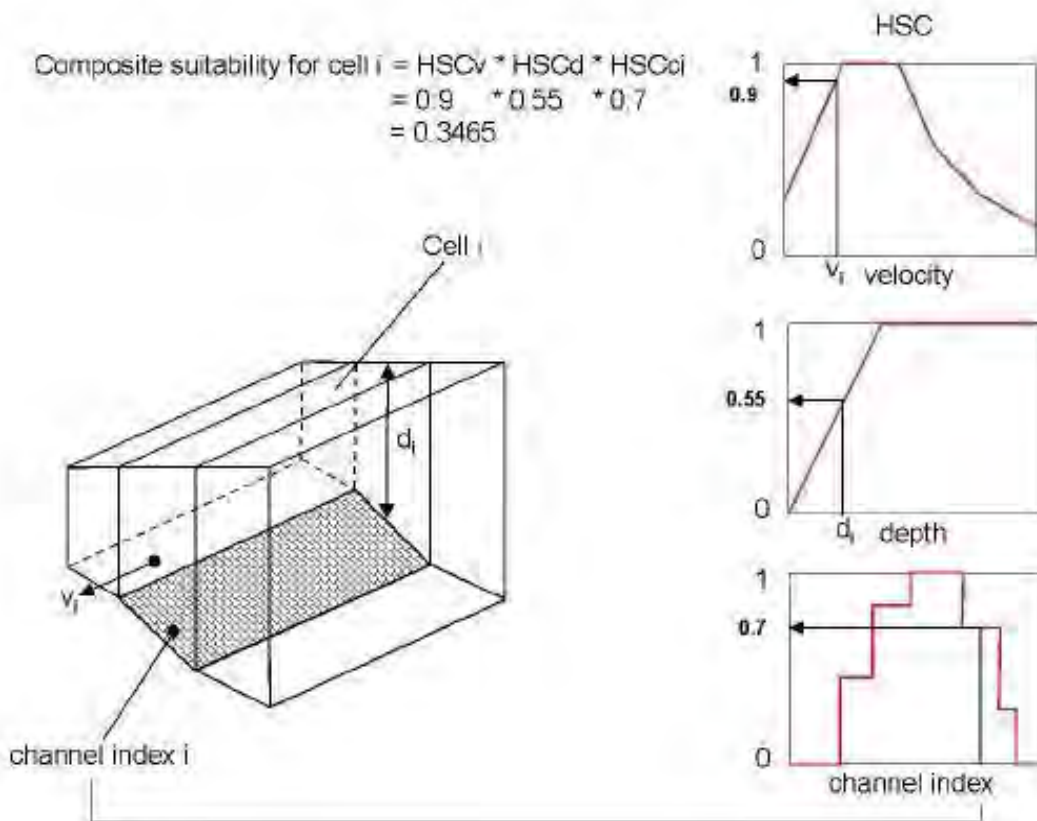
The habitat models rely on HSC relating hydraulic and channel characteristics to the habitat requirements of fish, other aquatic species, or even recreational activities. These HSC are used to describe the adequacy of various combinations of depth, velocity, and channel index conditions in each (or the adjacent) habitat computational cell to produce an estimate of the quantity and or quality of habitat in terms of surface area, bed area, or volume. As noted earlier, this metric is referred to as Weighted Usable Area (WUA) and has units of square feet per 1,000 linear feet of stream length (regardless of stream width). WUA is computed within the reach at a specific discharge from:

$$WUA = \frac{\sum_{i=1}^n A_i * C_i}{\text{Reachlength (1,000 feet)}}$$

where: A_i = surface area of cell i C_i = combined suitability of cell i (i.e., composite of depth, velocity and channel index individual suitabilities)

The combined suitability of the cell is derived from the component attributes of each cell (see Figure 4-1) which are evaluated against the species and life stage habitat suitability curve coordinates for each attribute to derive the component suitabilities as illustrated in Figure 4-5. Once the individual component suitabilities have been determined, the user has the option to select several different ways of aggregating them for a cell into a single composite cell suitability.

Figure 4-5. Habitat suitability criteria attributes for a habitat cell, showing multiplicative aggregation option.



The most common method is a multiplicative aggregation given by:

$$C_i = V_i * D_i * S_i \quad (4-2)$$

where: C_i = composite suitability of cell i V_i = suitability associated with velocity in cell i D_i = suitability associated with depth in cell i S_i = suitability associated with channel index in cell i

Second, the geometric mean can be used. This implies a compensation effect between the component suitability values. If two of three individual composite suitabilities are within the optimum range and the third is very low, the third individual composite suitability has a reduced effect on the computation of the composite suitability. The geometric mean is calculated as:

$$C_i = \sqrt[3]{V_i * D_i * S_i}$$

Third, the most locally limiting individual suitability composite suitability for the cell based on the according to:

$$C_i = \sqrt[3]{V_i * D_i * S_i} \quad (4-3)$$

factor can be selected by setting the minimum of the individual cell factors

$$C_i = \text{Min}(V_i, D_i, S_i) \quad (4-4)$$

Once the composite suitability C_i has been determined, then the amount of WUA using all cells at this specific discharge is computed according to the following equation:

$$n \text{ WUA} = \sum_{i=1}^n A_i * C_{i(4-5)}$$

where: WUA = total Weighted Usable Area in stream at specified discharge

C_i = composite suitability for cell i

A_i = vertical view area of cell i (bed area or volume)

This process is then repeated for all discharges simulated and the functional relationship between habitat and discharge as illustrated in Figure 4-5 is obtained. As will be discussed under the HABEF and HABTAM models, the WUA within a specific cell can also be “adjusted” based on the attributes of adjacent cells such as conditional velocities, or on the difference in attributes of the existing cell when compared over a range of paired conditions.

Basic Assumptions in Habitat Modeling

The habitat programs in general are based on the following assumptions:

1. Individual organisms select the most desirable conditions within a steady state stream but will use less favorable areas as the stream becomes more crowded.
2. Desirable conditions can be adequately represented by habitat suitability criteria curves.
3. Each cell can be evaluated independently.
4. The area weighted arithmetic sum of available habitat (as WUA) in each cell is indicative of total habitat conditions at a specific discharge.
5. Physical habitat (not water quality and/or other factors) is limiting the population size.

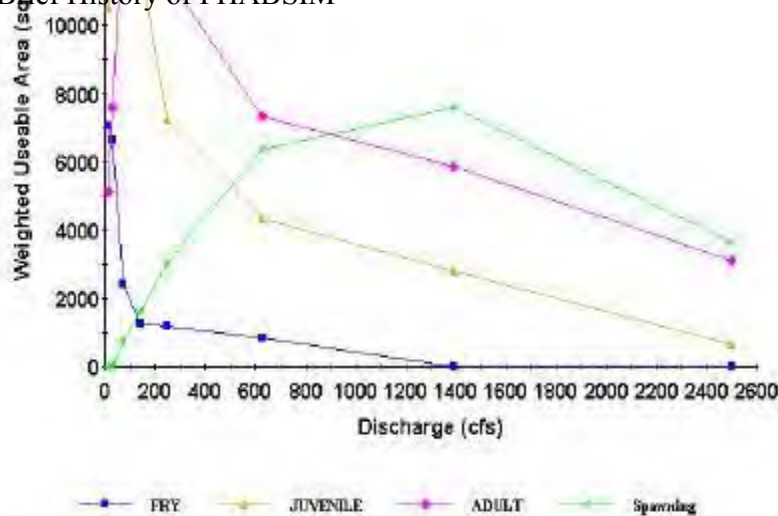
It should be emphasized that prediction of habitat as a metric (i.e., WUA) within PHABSIM is made in terms of changes to physical properties of aquatic microhabitat (i.e., velocity, depth, and channel index) and do not directly predict changes in the biomass of organisms. This fact has led to much criticism in the literature when PHABSIM results were applied and interpreted without consideration for other factors such as water quality, temperature, food availability, and fishing mortality. However, a number of studies have shown that there is a positive relationship between the output derived from PHABSIM and observed distribution and abundance of fish (e.g., Jowett, 1992; Railsback et al., 1995; Bovee et al., 1994; Nehring and Anderson, 1993).

Figure 4-6. Simulated habitat-discharge relation for Rainbow Trout.

The typical habitat-discharge relationship provided in Figure 4-6 represents the basic output from the habitat modeling phase of PHABSIM. Note that the goal of habitat time series and related project assessment methods in IFIM is to allow the user to integrate this information with the available data on existing and/or proposed alterations of stream flows in order to evaluate proposed

Windows		DOS	Difference	% diff
Cell bed elevation	HABTAE Flow/Habitat Relations	91.65	0	0.
Water surface elevation	RAINBOW TIE	92.47	0.014	0.
Depth		0.806	0.014	1.
Depth Suitability Index		0.0708	0.025	26
Combined Suitability Index		0.0644	0.023	26
Weighted Usable Area		8.698	3.096	26

Acknowledgements	i
PREFACE	ii
A Brief History of PHABSIM	



management alternatives. Further, the basic relationship between habitat and discharge, illustrated in Figure 4-6, is not the only analytical capability within PHABSIM for development of an understanding of the “controlling” factors, examination of the quality of total habitat, and evaluation of potential effects of alternative flow regimes. The other habitat simulation and analysis capabilities of PHABSIM are considered in the following section, which highlights the specific computational capabilities of each habitat program, and in the following chapter on applying PHABSIM within the IFIM Framework.

Habitat Modeling Options in PHABSIM

The following sections present each of the main habitat models, a description of their primary purpose, computational control options and the basics for their application. Table 4-2 provides an overview when a particular model might be used and distinctive options. The use of each of the main habitat models is also covered in the accompanying laboratory exercises as indicated at the beginning of the chapter.

at model descriptions. Use when these habitat results Other Model are desired Distinctive options comments

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

The Average Parameter Model AVDEPTH/AVPERM

The two general types of habitat modeling in PHABSIM are based on either average conditions in an entire stream channel or on distribution of velocity and depth among field measurement cells (i.e., habitat computational cells) and the

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

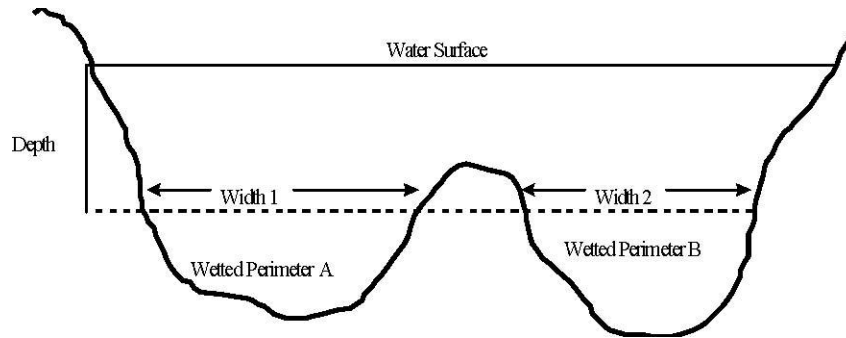
PREFACE

nature of the channel in a stream. The average parameter model AVDEPTH/AVPERM calculates wetted width and wetted surface for flows and water surface elevations supplied by the user. It determines width of a stream with water over a depth specified by the user. The average velocity is also calculated.

Wetted perimeter, wetted width, and average velocity have long been used as indexes to the physical habitat in a stream. In using the wetted width or wetted perimeter, the assumption is made that all the stream area is of equal value to the instream flow activity of interest. The wetted perimeter and wetted width will always either stay the same or increase with depth. The use of the AVDEPTH/AVPERM program can often provide valuable insights into the functioning of the hydraulic simulations at specific cross sections as well as for reach aggregated results and the associated implications to target species and life stages.

PHABSIM programs assume that the hydraulic variables measured at a cross section extend halfway to adjacent cross sections upstream and downstream. If this is not the case, upstream weighting factors should be applied.

The output resulting from AVDEPTH/AVPERM gives information for each cross section and a summary of the average parameters for a whole reach of stream including discharge, depth, cross sectional data, and velocity. In addition, for each of the specified depths (maximum of five), AVDEPTH and AVPERM calculate the total width of the stream that is at least as deep as the specified depth (see Figure 4-7). The use of wetted width is a special case of WUA habitat modeling in that the weights for habitat computational cells are essentially set to 1.0 for all velocities, depths, and channel indexes.



$$\text{AVDEPTH} = \text{WIDTH 1} + \text{WIDTH 2}$$

$$\text{AVPERM} = \text{WETTED PERIMETER A} + \text{WETTED PERIMETER B}$$

Figure 4-7.
Calculation of
width and wetted
perimeter in
AVDEPTH/AVP
ERM.

Running AVDEPTH/AVPERM

The AVDEPTH/AVPERM program is accessed from the PHABSIM for Windows interface using **/Models/AVDEPTH/AVPERM**. The depths to be evaluated are set in the **../Models/Avdepth/Avperm/Avdepth Avperm input** tab which also contains the run button.

If depths are specified, the AVDEPTH/AVPERM program will calculate the total width of the stream that is at least as deep as the depth(s) specified. Depths are entered in the table provided in the **../AVDEPTH/AVPERM Input** tab.

The HABTAE Program

The HABTAE program is the main habitat program in PHABSIM for Windows. It calculates WUA (surface or bed) or weighted usable volume (WUV) for a reach or for each cross section. Depending on the options selected to control the computations, output will contain: (1) WUA, (2) usable surface area (UA) (given a user specified minimum value for combined suitabilities), (3) usable volume (UV) and (4) WUV that is the WUA times the water depth. HABTAE now also contains the conditional or adjacent velocity calculations formerly contained in HABTAV. The adjacent velocity calculations in the HABTAE program simulate situations where fish habitat is determined by hydraulic parameters at the fish's location, as well as by velocities near the fish. (See Habitat Calculations Conditioned on Adjacent Velocities below.)

The user is reminded that the cell boundaries in HABTAE are defined as illustrated in Figure 4-8. HABTAE uses the

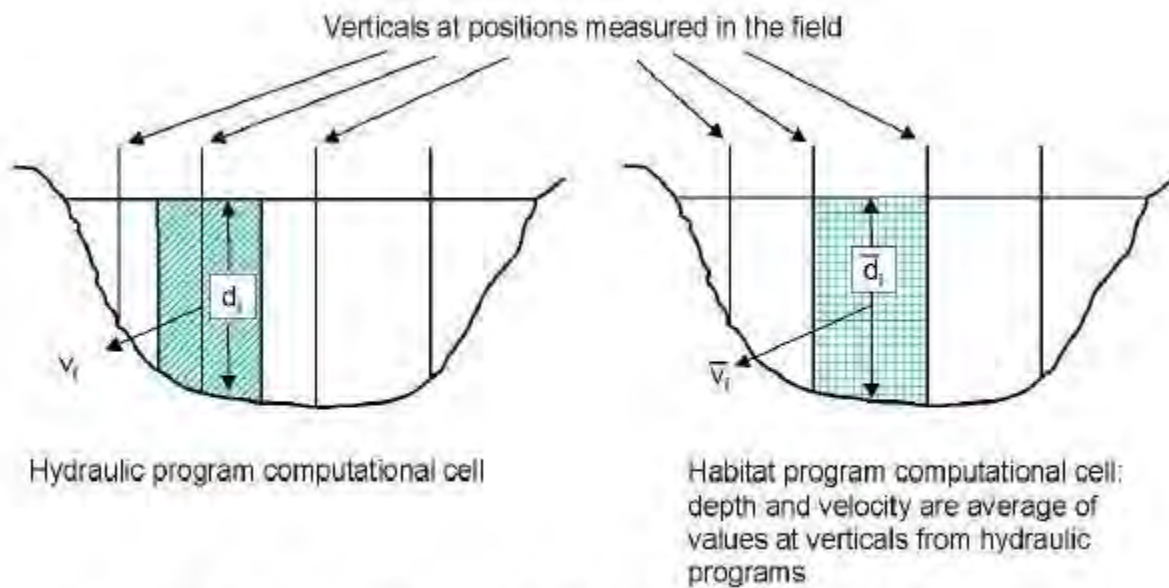


Figure 4-8. Cell boundaries in the hydraulic and habitat programs in PHABSIM.

channel index value taken from the X coordinate vertical on the upstream-right (not left) side of the cell. This should be kept in mind when entering data.

Figure 4-8. Cell boundaries in the hydraulic and habitat programs in PHABSIM.

The HABTAE program requires that HSC curves for aquatic species or recreational activities be created or imported using the **/Edit/Suitability Curves** menu and successful simulations of water surface profiles and velocity distributions be performed prior to habitat modeling.

Setting HABTAE Options

The HABTAE program uses the options selected in the following tabs under **/Models/Habtae**: **../Output Options**, **../Computations**, **../Limits**, **../Adjacent Velocity**, and **../Velocity Replacement Options**. HSC data must have been provided in **/Edit/Suitability Curves**, and the appropriate hydraulic programs must have been run. The user must select the HABTAE options prior to running the model. The options in the HABTAE program are summarized in Table 4-3. Note that due to enforcing use of the same habitat cell definition across all habitat programs in PHABSIM for Windows, the options formally in the HABTAV program in the DOS version are now contained in HABTAE. Conditional velocity simulations within the HABTAE program are controlled by the combination of selected options for scanning for VLIM and using VLIM and the action to be taken when VLIM is not found. The first option in the **/Models/HABTAE/Adjacent Velocity** tab directs the program to scan the cross section a user-specified distance out

from the cell for which the habitat is being simulated to locate a user-specified velocity in any adjacent cells. If the velocity is found within this distance, the WUA calculated for the cell is multiplied by one (1.0). In other words, the existing cell WUA remains unmodified. Note that the program can be directed to use the limiting velocity as a minimum or maximum limit. If the user-specified velocity is not found, the WUA calculation when VLIM is not found option directs the program to scan the cross section a second time for an initial velocity. This initial velocity is the first velocity where fish habitat is worth more than zero (0.0) based on the suitability criteria. The program then searches for a velocity, which is between the initial velocity and the user-specified velocity that is closest to the user-specified velocity and then interpolates the velocity suitability value using the suitability curves and the located velocity. This new suitability value is multiplied by the original WUA to obtain a new amount of WUA for the current cell.

Description of Habitat Calculation Options

Several of the options shown in Table 4-3 are self-explanatory. However, others bear further elaboration to ensure clarity as follows.

ZHAQF Options

The **ZHAQF Options** radio buttons in the **Output Options** tab determine the mode of calculation of habitat area. The user may elect to calculate Weighted Usable Area or volume or simply usable area or volume. The weighted usable habitat can be surface area, bed area, or volume. The usable area is all areas with a composite suitability factor greater than 0.001. Volumes are calculated by multiplying weighted cell areas by the depth. Typical PHABSIM applications select “Write WUA or WUV” in the ZHAQF Options portion of the **Output Options** tab and “Calculate WUA for reach” in the **Computations** tab. Note: take care to match WUA or UA in the **Output Options** tab with the option selected in the **Computations** tab.

Using Bends

The **Describe Reach Bends** check box in the **Computations** tab allows the length represented by a cross section to vary from cell to cell (also called variable cell length) across the stream (i.e., a bend). The default is to use cells as rectangles in plan view. Most historical PHABSIM applications have used this default. Supplying the additional information for bends allows a more accurate representation of a study site where bends are significant.

When the **Describe Reach Bends** box is checked, the program uses cells as trapezoids based on the length multiplied by left and right bank weights. To use this option, left and right bank weighting factors must be entered in **/Edit/Cross Sections**. Note that the left and right bank weighting factors are multiplied times the cross section length entered in the second column of the cross section data in **/Edit/Cross Sections**. Thus, one bank should have a weight greater than 1.0 and the other should be less than 1.0 to indicate a bend in the stream. When the longitudinal distances between head pins were measured in the field, it is straightforward to find the ratio of left and right bank weights to the cross section length. If these distances are not known, it may be possible to approximate the distances if accurate maps of the study site are available. The check box must be checked and

Table 4-3. Options in the HABTAE program.

Option description	Action when set to indicated value, notes
Output Options Tab Write Flow Data (check box) (IOC 3)	
Output Options Tab Write Computational Details (check box) (IOC 4)	
Output Options Tab Write Cross Section Data (check box) (IOC 2)	
Output Options Tab ZHAQF Options (radio buttons) (IOC 10)	
Output Options Tab Discharges (input table)	
Computations Tab Describe Reach Bends (check box) (IOC 12)	
Computations Tab Use a Minimum Contiguous Width (check box) (IOC 11)	
Computations Tab Use Zero CI in Calculations (check box) (IOC 18) box.	Writes the flow related data for each cross section evaluated at each discharge to ZOUT. It also lists the velocity for each cell that has water in it. The data are a rehash of the hydraulic model results. Recommend leaving blank unless a printed record is needed.
	Writes all the computational details used in determining the weighted usable area, weighted usable bed area, or weighted usable volume to ZOUT. Recommend leaving blank except when details are needed to evaluate the simulation. Strongly recommend using only a few life stages and discharges when using this option.
	Writes cross section data to ZOUT. Output is the same as that contained in /Edit/Cross Sections . Recommend leaving blank unless a printed record is needed.
	Determines calculation of habitat area. The weighted usable habitat can be surface or bed area or volume. The usable area is all areas with a composite suitability factor greater than 0.001. Typical applications select “Write WUA or WUV”. Take care to match WUA or WUV with the options selected in the Computations tab.
	User selects which of the discharges used in the hydraulic simulations are to be used for habitat calculations. Default is to use all discharges.
	Allows the length to vary from cell to cell (variable cell length) across the stream (i.e., a bend). Default is to use cells as rectangles in plane view. When checked, program uses cells as trapezoids based on the length multiplied by left and right bank weights. To use this option, left and right bank weighting factors must be entered in /Edit/Cross Sections .
	When checked this directs HABTAE to use a minimum contiguous width. Minimum width (WMIN) values must be supplied for each HSC curve set ID Number (life stage) in the right-hand table in the Velocity Replacement Options tab.
	This defines how channel index values of zero (0) are used. If not checked channel index values of zero are converted to 1.0 which effectively removes channel index from the calculation for any cell with a 0.0 CI. When checked, a channel index value of zero is used in the calculation of WUA for that cell. Recommend checking this Table 4-3 . Continued.

Option description Action when set to indicated value, notes

Computations Tab

Near Shore Habitat Analysis

(check box and distance entry box (IOC 22)

Computations Tab **WUA Calculations** (radio buttons) (IOC 1)

Computations Tab **Habitat Calculations** (radio buttons) (IOC 9) These are the typical habitat calculations produced by PHABSIM. Note that the outcome of these calculations is influenced by the other option choices.

Limits Tab **Velocity Limits** (radio buttons) (IOC 15)

Limits Tab

Minimum Effective Composite Suitability Factor (radio buttons) (IOC19) Use to prevent very small CF from accumulating a large area of poor habitat.

Velocity Replacement Options Tab **CFMIN**(column in input table)(IOC19)

Used to define suitable habitat for organisms that require certain combinations of depth and velocity within a given distance of the shoreline. These may be terrestrial as well as aquatic organisms.

Determines if the WUA, WUV, or weighted usable bed area (WUBA), is to be calculated, and if the WUA, WUV, or WUBA is to be calculated for an independent cross section or for a reach.

Controls how the calculation of habitat area will be made. **Standard calculation** -- Combined Suitability Factor (CF) = $f(v) * g(d) * h(ci)$, where: $f(v) * g(d) * h(ci)$ = variable preferences for velocity, depth and channel index.

Geometric Mean - CF = $(f(v) * g(d) * h(ci))^{0.333}$. **Lowest Limiting**

Parameter - CF = MIN($f(v)$, $g(d)$, $h(ci)$).

Limits the velocities allowed in the habitat simulation calculations. Choices are: No restriction on velocities; Abort if velocities are <0 or >15; and Convert negative velocities and abort if >15.

Sets a minimum composite suitability for each life stage. The minimum value for each life stage is entered in the CFMIN column in the right-hand table in the **Velocity Replacement Options** tab. When values less than CFMIN are calculated for a cell, the composite suitability for that cell is set to zero.

Data entry location for minimum effective composite suitability Factor.

Table 4-3. Continued.

Option description Action when set to indicated value, notes

Velocity Replacement Options Tab **Vel Calc** (column in input table) (IOC14) Where various Vel Calc options require additional input parameters, those parameters are supplied in the appropriate columns of the left or right

side input tables in the **Velocity**

Replacement Options tab.

Velocity Replacement Options tab **Dnose, a, b, n, D65** (columns in input table)

Velocity Replacement Options tab **Nose Vel** (column in input table) (IOC16)

Nose depth is supplied in Dnose field of right-hand table.

Note: If **Nose Vel** is not set to 0 for a life stage, **Vel Calc** should also be non-zero. Note: For **Nose Vel** options 1, 2, and 3, **Vel Repl** should be set to 0.

0 = Mean column velocity. 1 = Nose velocity - Empirical equation based a power law equation and user defined coefficients. User supplies the nose depth (Dnose) for which a velocity is to be calculated, and the calibration parameters A and B. These values are entered in the right input table. 2 = Nose velocity - 1/7th power law equation. User supplies nose depth (Dnose) in right input table. 3 = Nose velocity - logarithmic velocity distribution equation. The nose depth and the D65 of the bed material are supplied by the user in the right input table (scroll table to display D65).

0.1667

4 = Nose velocity - 1/mth power law equation. m is calculated using the equation: $m = \frac{c}{D^n}$, n is the Manning's roughness coefficient (n), and c is 0.105 for traditional units and 0.128 for metric units. The value of m is determined for each cell. The value of n and the nose depth are supplied in the right input table. 5 = Nose velocity - 1/mth power law equation. Same as above except m is calculated using the equation $m = aD^b$. Values for a and b and nose depth are supplied in the right input table. 6 = Nose velocity - 1/mth power law equation. Same as above except the nose depth (Dnose) is measured from the surface. The values for nose depth and n are entered in the right input table. 7 = Nose velocity = Shear velocity. To calculate the shear stress (θ), the Manning's roughness must be known. Manning's n is entered in the right input table.

Data entry location for nose depth, a and b coefficients, D65 sediment size and Manning's n from above.

0 = Given velocities, or nose velocities, (depending on what Vel Calc was set to) are used for habitat simulation. 1 = Optimum velocities are used for habitat simulation with equal depth from top as from bottom. Nose depth is set by one of two methods:

- (a) Dnose in the right-hand table of the Velocity Replacement Options tab; or
- (b) if Dnose has not been set, nose depth = .1.

2 = Optimum velocities are used for habitat simulation with unequal depth from top as from bottom. 3 = Mean velocity in a top cell is used in habitat simulation. The velocity used is the mean velocity found in a cell defined between the surface of the water column and the depth specified in the cell field in the right-hand table in the Velocity Replacement Options tab.

Table 4-3. Continued.

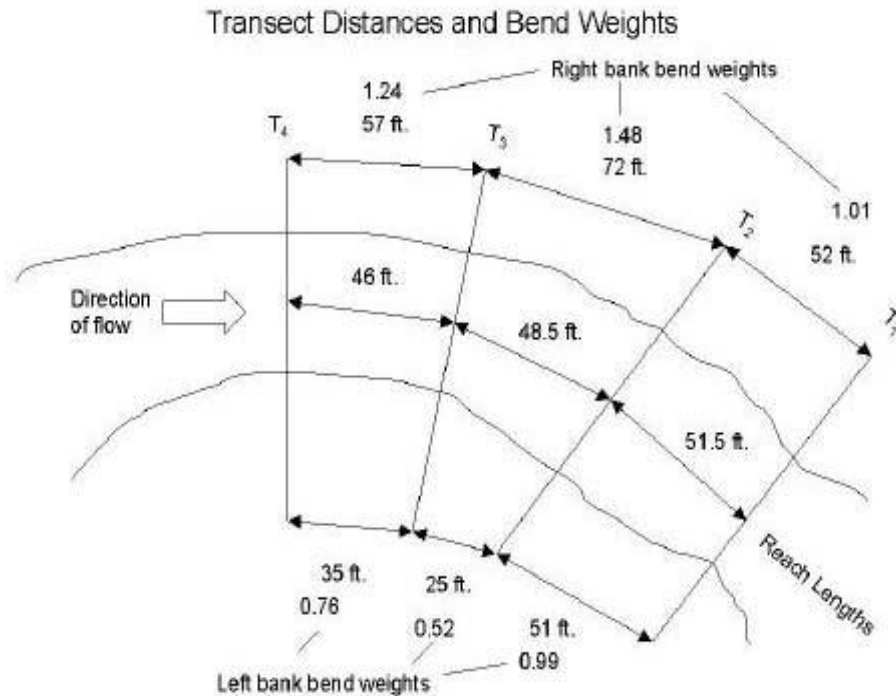
	Option description	Action when set to indicated value, notes
Velocity Replacement Options tab Vel Repl (column in input table, scroll to view Vel Repl column)(IOC17)		Data entry location for specific gravity of the bed material.
If Vel Repl is not 0, then Nose Vel must be 0.		Permitted combinations of velocity replacement options are shown in the table at the bottom of the combinations shown can be used.
If Vel Repl is 1 or 2, then Vel Calc must be 0. If Vel Repl is 3, then Vel Calc must be set to 7 and Manning's n, D65 of bed material, and the specific gravity must be entered in the right-hand table of the Velocity Replacement Options tab. If specific gravity is not specified, 2.65 is used.		When checked, HABTAE performs adjacent velocity scanning and applies the criteria selected in VLIM as box (below).
Velocity Replacement Options tab Sp. Grav. (column in input table)		$\sqrt{gd}$ where: V = velocity, g = acceleration of gravity, and d = depthgd
Velocity Replacement Options tab		
Adjacent Velocity tab Scan for velocity in adjacent cells (IOC-V 1) (checkbox) 0 = Use given velocity. 1 = Use velocity * depth as velocity. 2 = Use (velocity**2) * depth as velocity 3 = Use Shield's Parameter as velocity.		
	τ K _s = where: K _s = Shield's parameter, 9 = shear stress on a bed, D ₆₅ = size of bed D ₆₅ (S _s -1) γ	
	surface material at which 65% are smaller, S _s = specific gravity of the bed material, and (= unit weight of water. 4 = Use Froude number as velocity.	
	V F _r =	

Table 4-3. Concluded.

icated val

Option description	Action when set to
Adjacent Velocity tab ☐ Minimum - Scans adjacent cells within a user-defined distance (DIST) for velocity greater than or equal to a Use VLIM as (IOC-V 1) user-defined minimum velocity (VLIM). That is, VLIM acts as a lower bound. If found, WUA for current cell = (Radio buttons) WUA * 1.0.	
• Minimum - Scans adjacent cells within a user-defined distance (DIST) for velocity greater than or equal to a user-defined minimum velocity (VLIM). That is, VLIM acts as a lower bound. If found, WUA for current cell = WUA * 1.0.	
• Maximum - Scans adjacent cells within a user-defined distance (DIST) for velocity less than or equal to a user-defined maximum velocity (VLIM). That is, VLIM acts as an upper bound. If found, WUA for current cell = WUA * 1. 0. VLIM, DIST, and V0 are supplied in the input table on the Adjacent Velocity tab.	
Adjacent Velocity tab ☐ WUA = 0 - If VLIM is not found in adjacent cells, set WUA for current cell to zero. WUA calculation when ☐ Scan for initial Velocity (V0) and interpolate – If VLIM is not found in adjacent cells, the program scans a VLIM not found (IOC-V 5) second time for an initial velocity, V0 , which is the first velocity where fish habitat is greater than 0. (Radio Buttons) Then it searches for a velocity between V0 and VLIM which is closest to VLIM and interpolates a multiplier for the WUA for the current cell between 0.0 and 1.0 based on the velocity found by this process.	
Adjacent Velocity tab Table where DIST, VLIM, and V0 are supplied by the user. Scan distance, velocity limit, initial velocity (input table with these columns)	

the left and right bank weights must be set greater than 1.0 on the long bank and less than 1.0 on the short bank for this



option to have an effect. Figure 4-9 illustrates bend weights.

Figure 4-9. Illustration of bend weights.

Note: In PHABSIM the bend weights act like the upstream reach length weighting factors. That is, they are applied upstream from the cross section. In this example, the left bank bend weight for the third cross section would be calculated from the field data as 35 ft divided by 46 ft. So 0.76 would be entered in the **L Bank WF** field of the **/Edit/Cross Data** tab. When bends are included in the habitat calculation, the final weight applied to habitat cells in the cross section is a composite of the bend weights and the upstream weighting factors for the current and the downstream cross section. This is due to the fact that the habitat cell length for cross section B is a combination of one minus the upstream weighting factor for cross section A times the length from B back to A and the upstream weighting factor for cross section B times the length from C back to B. Refer back to Figure 4-3 of use of upstream weighting factors and reach length.

Using Minimum Contiguous Width

If a species requires a minimum amount of continuous habitat across the stream for the habitat to be usable, this option allows the program to enforce that requirement. When checked, this option in the **Computations** tab directs HABTAE to only count habitat in a cell if it is part of an area that has a minimum contiguous width of suitable habitat. Minimum width (WMIN) values must be supplied for each HSC curve set ID Number (life stage) in the right-hand table in the **Velocity Replacement Options** tab.

Use of a Zero Channel Index Value The **Zero CI in Calculations** check box in the **Computations** tab defines how channel index values of zero (0) are used. When PHABSIM was first developed, channel index values of zero were considered to mean that no information was available. This option allows the user to select how a CI of zero is to be treated. If this box is not checked, channel index values of zero are converted to 1.0, which effectively removes channel index from the calculation. When checked, a channel index value of zero is used in the calculation of WUA for that cell. Care should be taken to ensure that this option reflects the analyst's desired outcome. Recommend checking this box for most applications unless it is known that zero values indicate that channel index is to be ignored.

Near Shore Habitats

The **Near Shore Habitat Analysis** check box and distance entry box in the **Computations** tab is used to define suitable habitat for organisms that require certain combinations of depth and velocity within a given distance of the shoreline. These may be terrestrial as well as aquatic organisms. This option was developed to describe habitat for a water snake that required riffle habitat near basking areas on the shore. Other possibilities include riparian bird species that need feeding areas within a certain distance of the shoreline.

To use this option, check the **Near Shore Habitat Analysis** box and supply the distance from shore that habitat will be counted. All cells more than the specified distance from shore will be eliminated from the habitat sum. As the shoreline moves with higher or lower water surface elevations, different cells will fall within the near shore distance and the habitat value will vary according to the depth, velocity, and channel index combinations in those cells. Note the HSC used in this analysis may actually be HSC for the food organisms of the target species; for example the water snake's preferred prey.

Weighted Usable Area Calculations and Independent Cross Sections

The **WUA Calculations** radio buttons in the **Computations** tab are used to select the most commonly used calculation schemes in PHABSIM. They determine if WUA, WUV, or weighted usable bed area (WUBA), is to be calculated, and if the WUA, WUV, or WUBA is to be calculated for independent cross sections or for a reach. While the selection of WUA, WUV, or WUBA is straightforward, the use of independent cross section or reach aggregation merits further discussion.

Most PHABSIM applications use aggregation of the WUA by reach and result in one habitat-flow relation for each species/life stage for the entire reach. However, this approach assumes the reach length weighting factors accurately capture the desired weighting for each cross section. If the weighting factors are a concern, or if alternate weighting schemes are to be considered in the analysis, calculating WUA for each cross section independently allows the user to perform other analyses outside of PHABSIM for Windows. When using the independent cross section option, the user is advised to take care in tracking the tables of WUA carefully.

The Form of the Habitat Calculation

The **Habitat Calculations** radio buttons in the **Computations** tab direct the form of the habitat calculation. These choices allow the user to select among standard, geometric mean, or minimum parameter calculations. Note that the outcome of these calculations is influenced by the other option choices.

In the standard calculation the combined suitability factor is:

$$(CF) = f(v) * g(d) * h(ci) \quad (4-6)$$

where: $f(v) * g(d) * h(ci)$ = variable preferences for velocity, depth, and channel index.

This is a simple multiplication of the velocity, depth, and channel index HSC weights and implies synergistic action. It also treats each of the three variables as independent. That is, there are no interaction terms in the multiplication. Optimum habitat only exists if all variables are optimum and low SI values for all three variables can

yield very low WUA values for a cell. The geometric mean produces a combined suitability using:

$$CF = (f(v) * g(d) * h(ci))^{0.333} \quad (4-7)$$

This technique implies compensatory effects; if two of the three variables are in the near-optimum range, the value of the third variable has less effect, unless it is zero. This option may be selected for organisms that fare well in marginal habitats as long as two of the physical habitat parameters are high.

The lowest limiting parameter approach calculates combined suitability as:

$$CF = \text{MIN} (f(v) * g(d) * h(ci)) \quad (4-8)$$

This approach determines the composite suitability factor as the value of the most restrictive variable. This implies a limiting factor concept (i.e., the habitat is no better than its worst component), but is limited only by its worst element. The user is advised to select the habitat calculation form with care based on the available data on the species of interest and the decision environment in which the PHABSIM results will be used.

Velocity Limits and Eddies

The **Velocity Limits** radio buttons on the **Limits** tab allow the user to limit the velocities allowed in the habitat simulation calculations. The choices are: **No restriction on velocities**, **Abort if velocities are <0 or >15**, and **Convert negative velocities and abort if > 15**. MESC strongly recommends selecting the second or third button. If the "No restrictions" option is required for successful habitat simulation runs, there probably was an error in the hydraulic simulation process.

The "Convert negative velocities" option would apply in situations where reverse flow occurs on part of a transect, such as a transect that runs across an eddy. Care should be taken in such situations to select the calibration velocity set that applies to this situation and not to extrapolate reverse flow to discharges where either the eddy has not yet developed or where it has been washed out at higher flows.

Minimum Effective Composite Suitability

The **Minimum Effective Composite Suitability Factor (CFMIN)** radio buttons in the **Limits** tab allow the user to prevent very small composite suitabilities from accumulating a large area of poor habitat. This option sets a minimum composite suitability for each life stage. The minimum value for each life stage is entered in the **CFMIN** column in the right-hand table in the **Velocity Replacement Options** tab. When a value less than **CFMIN** is calculated for a cell, the composite suitability for that cell is set to zero.

Nose Depth: Empirical Calculation of Velocity at a Given Depth

The **Vel Calc** column in the input table in the **Velocity Replacement Options** tab allows various forms of empirical or assumed vertical velocity distributions to be applied to determining the habitat value based on assuming the organism selects a particular location above the stream bed. This option is particularly useful when the depth-oriented behavior of a particular life stage of a target species is known. Thus, the velocity calculation option varies by HSC curve number as shown in the left-hand table of the **Velocity Replacement Options** tab.

When **Vel Calc** is set to zero (0), only the mean column velocity is used in habitat calculations. This is the default or standard habitat calculation.

When **Vel Calc** is set to 1, nose velocity is calculated using an empirical exponential equation and user-defined coefficients. The user supplies the nose depth (D_{nose}) for which a velocity is to be calculated, and the calibration parameters a and b. These values are entered in the right input table. Nose velocity is calculated as:

$$V_n = Va \left[\frac{D_{nose}}{D} \right]^b \quad (4-9)$$

where: V = mean column velocity of the cell, and D = total depth of the cell.

When **Vel Calc** is set to 2, nose velocity is calculated using the Prandtl-von Karman 1/7th power law equation. User supplies nose depth (D_{nose}) in right input table (scroll table to display D_{nose}). Nose velocity is calculated as:

$$V_n = V(1 + 1/7) \left[\frac{D_{nose}}{D} \right]^{1/7} \quad (4-10)$$

When **Vel Calc** is set to 3, nose velocity is calculated using a logarithmic velocity equation. The nose depth and the D_{65} of the bed material are supplied by the user in the right input table (scroll table to display D_{65}). The relationship is given as:

$$V_n = V \frac{\log(33.2 * d_{nose}/D_{65})}{\log(12.12 * d_{nose}/D_{65})} \quad (4-11)$$

When **Vel Calc** is set to 4, nose velocity is calculated using a 1/mth power law equation. The nose velocity equation used is:

$$V_n = V(1 + 1/m) \left[\frac{D_{nose}}{D} \right]^{1/m} \quad (4-12)$$

and m is calculated using: c

$$m = \frac{0.1667}{c} D^n \quad (4-13)$$

where: n = Manning's roughness coefficient, and c = 0.105 for traditional units and 0.128 for metric units. The value of m is determined for each cell. The value of n and the nose depth are supplied in the right input table (scroll table as needed to display n).

When **Vel Calc** is set to 5, nose velocity is calculated using the 1/mth power law equation in the same manner as above except m is calculated using:

$$m = aD^b \quad (4-14)$$

Values for a and b and nose depth are supplied in the right input table (scroll table to display D_{nose}).

When **Vel Calc** is set to 6, nose velocity is calculated using the 1/mth power law equation in the same manner as above except the nose depth (D_{nose}) is measured from the surface. The values for nose depth and n are entered in the right input table (scroll table to display D_{nose}).

When **Vel Calc** is set to 7, shear velocity is used for nose velocity. To calculate the shear stress (θ), the Manning's roughness must be known. Manning's n is entered in the right-hand input table (scroll table to display n). Then:

t

$$\sqrt{\frac{t}{\rho}} \quad (4-15)$$

$$\mu^* = \frac{\tau}{\rho}$$

where: μ^* = shear velocity, τ = shear stress on the bed, and ρ = density of water.

Replacements for Velocity

The **Vel Repl** column in the left input table of the **/HABTAE/Habitat Simulation/Velocity Replacement Options** tab allows the user to make certain replacements for velocity in the velocity calculation algorithm. These replacements enable alternative habitat determinations when sufficient data is available to support their use. All velocity replacement option combinations are subject to the conditions stated at the end of this section.

When using velocity replacements the analyst must take care to ensure that the habitat suitability criteria for velocity reflect the velocity replacement option being used. That is, new HSC must be entered in **/Edit/Suitability Curves** corresponding to the velocity replacements described below. In the option tables in the **Velocity Replacement Options** tab, a different set of velocity calculation options may be supplied for each habitat suitability criteria curve. Thus, an analysis can be performed where most HSC are treated with the standard mean column velocity calculation and certain HSC are used with velocity replacements. This means that the user must be cautious to ensure that the velocity HSC values are Froude number suitability values if **Vel Repl** is set to 4 (see below) for a particular HSC curve set.

When **Vel Repl** is set to 0, the velocity option specified by **Vel Calc** is used.

When **Vel Repl** is set to 1, the product velocity * depth is used as velocity.

When **Vel Repl** is set to 2, (velocity**2) * depth is used as velocity.

When **Vel Repl** is set to 3, Shield's Parameter is used as velocity.

Shield's parameter is defined as:

$$K_s = \frac{\tau}{\rho} \frac{1}{D_{65} (S_s - 1) g} \quad (4-16)$$

where: K_s = Shield's parameter, τ = shear stress on a bed, D_{65} = size of bed surface material at which 65% are smaller, S_s = specific gravity of the bed material, and τ = unit weight of water. Values for D_{65} and specific gravity are supplied in the right input table (scroll table as needed to display **D₆₅** and **Sp. Grav.**). If the user does not supply specific gravity, 2.65 is used. When **Vel Repl** is set to 4, Froude Number is used as velocity. Froude number is defined as:

$$Fr = \frac{V}{\sqrt{gd}} \quad (4-17)$$

where: V = velocity, g = acceleration of gravity, and d = depth.

The following conditions apply to combinations of **Vel Repl** and **Nose Vel**. If **Vel Repl** is not 0, then **Nose Vel** must be 0. If **Vel Repl** is 1 or 2, then **Vel Calc** must be 0. If **Vel Repl** is 3, then **Vel Calc** must be set to 7 and Manning's n , D_{65} of bed material, and the specific gravity must be entered in the right-hand table of the **Velocity Replacement Options** tab. The permitted combinations of **Nose Vel**, **Vel Repl**, and **Vel Calc** are given in a table

at the bottom of the **Velocity Replacement Options** tab.

Nose Depth: Use of “Optimum” Velocities for a Portion of the Water Column

The **Nose Vel** column in the input table in the **Velocity Replacement Options** tab allows the analyst to select the portion of the water column where velocities will be calculated. The velocity calculated in the selected portion of the water column is sometimes referred to as an “optimum” velocity. Note: if **Nose Vel** is not set to 0 for a life stage, **Vel Calc** should also be non-zero. Further, for **Nose Vel** options 1, 2, and 3, **Vel Repl** (see below) should be set to 0.

When **Nose Vel** is set to 0, the simulated mean column velocities, or nose velocities, (depending on what **Vel Calc** was set to) are used for habitat simulation.

When **Nose Vel** is set to 1, optimum velocities are used for habitat simulation with equal depth from top as from bottom as follows: A “top of cell and bottom of cell” are removed from the water column. Within the remaining water column, the velocities in the habitat simulation calculations are optimized, i.e., it is assumed that the fish can move vertically to find the "best velocity" in the remaining water column. This "best velocity" is used with the nose velocity calculated by the selection of **Vel Calc**. If **Vel Calc** = 0, and **Nose Vel** = 1 or 2, the program will calculate nose velocities as if **Vel Calc** = 2. The "optimum (best) velocity" is defined as the velocity that is found within the range of nose depth down from the surface (top) and nose depth up from the bottom that has the highest suitability index value on the HSC relation for that species/life stage. Nose depth is set by one of two methods, (a) **Dnose** in the right-hand table of the **Velocity Replacement Options** tab, or (b) if **Dnose** has not been set, nose depth has a default value of 0.1.

When **Nose Vel** is set to 2, optimum velocities are used for habitat simulation with unequal depth from top as from bottom. The top portion of the cell that is removed is the distance between the water surface and the depth specified in the **Cell** field in the right-hand input table in the **Velocity Replacement Options** tab (scroll the table to find the **Cell** column). The bottom portion of the cell that is removed is defined by the **Dnose** values.

When **Nose Vel** is set to 3, the mean velocity in top portion of each a top cell is used in habitat simulation. The velocity used is the mean velocity found in the region of the cell defined between the surface of the water column and the depth specified in the **Cell** field in the right-hand table in the **Velocity Replacement Options** tab.

Habitat Calculations Conditioned on Adjacent Velocities

In some situations, fish habitat is determined not only by hydraulic parameters at the fish’s location, but also by velocities near the fish. The adjacent velocity calculations in HABTAE provide a mechanism for lateral scanning of velocity conditions that can be used to evaluate such phenomena as feeding stations. Each cell on a cross section is evaluated for its proximity to desired nearby velocity conditions. The habitat in each cell is included in the total WUA when the desired adjacent velocity conditions are met and excluded when those conditions are not met. The adjacent velocity calculations are controlled by a checkbox that determines if adjacent velocity calculations are to be performed and by combinations of the following menu items in the **Adjacent Velocity** tab. When adjacent velocity scanning is performed, the program starts at the center of the current cell and scans in both directions to find velocities that satisfy the adjacent velocity conditions.

Simulation of a feeding station would take the following form: Velocity HSC for the target species would indicate that habitat was most suitable in the low velocity range expected to be found behind a rock or other cover object. The adjacent velocity criteria would search for a significantly higher velocity within the sight distance of the species using the minimum adjacent velocity criteria (the **Use VLIM as Minimum** radio button in the **./HabtAE/Adjacent Velocity** tab). For example, if the “feeding” velocity HSC for a species peaked at 0.5 fps, the VLIM value was 2 fps, the search distance was 3 ft and the minimum adjacent velocity criteria caused the program to search for velocities within 3 ft that were greater than 2 fps, the program would sum habitat for only cells that had low velocities within 3 ft of high velocities. The paragraphs below describe how to set up adjacent velocity calculation options.

Selecting the Form of the Adjacent Velocity Calculation

Figure 4-10 shows the computational options within the HABTAE program based on conditional velocity simulations. The options are discussed below.

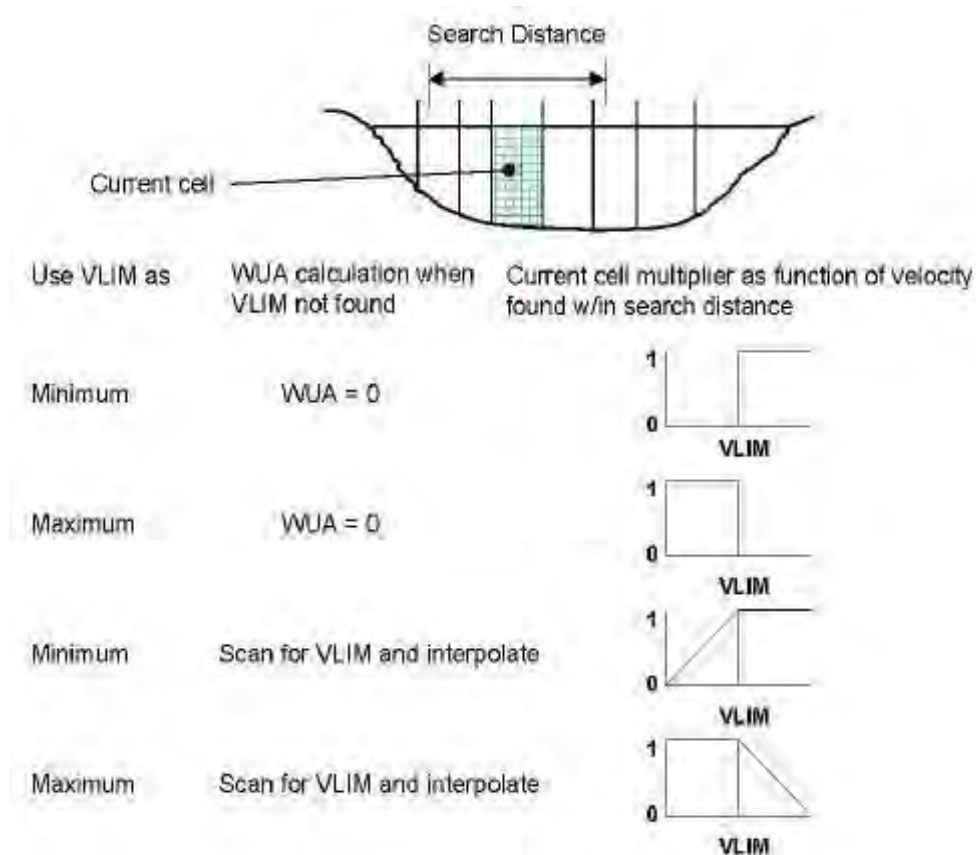
The **Use VLIM as** radio button selection allows the user to choose if a minimum or maximum adjacent velocity limit is to be scanned for when the **Scan for velocity in adjacent cells** box is checked. When **Minimum** is selected, the program scans adjacent cells within a user-defined distance (**DIST**) for velocity greater than a user-defined velocity value (**VLIM**). That is, the limiting velocity acts as a minimum. If a velocity greater than VLIM is found, WUA for the current cell is retained by multiplying original WUA * 1.0. When **Maximum** is selected, the program scans adjacent cells within the user-defined distance (**DIST**) for a velocity less than or equal to the user-defined velocity (**VLIM**). If a velocity less than VLIM is found, WUA for the current cell is retained by multiplying WUA * 1.0.

Cells containing the desired minimum or maximum velocity may not be encountered when evaluating adjacent cells within the scan distance DIST. The **WUA calculation when VLIM not found** options provide for dealing with this situation by either setting the current cell WUA to 0 or by interpolating a scaled value of the WUA when no cell within DIST of the current cell satisfies the VLIM constraint. The **WUA = 0** option directs the program to set the WUA in the current cell to zero if the appropriate minimum or maximum velocity is not found in adjacent cells within the scan distance. The **Scan for initial Velocity (V0) and interpolate** option directs the program to scan adjacent cells a second time using a relaxed velocity limit, **V0**, and searches for the adjacent cell velocity that exceeds (or falls below) **V0** by the greatest amount. The program then interpolates a multiplier for the WUA for the current cell between 0.0 and 1.0 based on the velocity found by this process. The multiplier is calculated as:

$$\text{Mult} = \frac{V_{\text{found}} - V_0}{(4-18) \text{ VLIM} - V_0}$$

Then the WUA for the current cell is calculated as the original WUA * Mult.

Figure 4-10. Illustration of adjacent velocity VLIM calculation options in HABTAE.



A caution on the different combinations of adjacent velocity options:

- If **Scan for velocity in adjacent cells** is checked, **Use VLIM as** is set to **Minimum**, the **WUA = 0** radio button is selected, and **V0** is greater than **VLIM**, it is illogical to supply a **V0**. These settings do not have the same result as **VLIM** nor **V0** being found in adjacent cells, hence, **V0** is ignored.
- Similarly, if **Scan for velocity in adjacent cells** is checked, **Use VLIM as** is set to **Maximum**, the **WUA = 0** radio button is selected, and **V0** is less than **VLIM**, it is illogical to supply a **V0**. These settings also result in neither **VLIM** nor **V0** being found in adjacent cells so **V0** is ignored.

Adjacent Velocity Calculation Example

While most of the habitat calculation processes are relatively straightforward, the adjacent velocity calculations merit an example to illustrate the process. Assume the adult life stage of a trout species can be assigned a search distance (**DIST**) of 10 ft. and a velocity threshold (**VLIM**) of 2.7 ft. per second. Further, assume the velocity threshold is treated as a lower bound (minimum) such that the purpose of the simulation is to find velocities that are above the minimum within the search distance from each cell. How is the habitat for a cell determined? Figure 4-11 shows the velocity distribution for cross section 0.0 of the sample study site at a discharge of 139 cfs. Consider the cell spanning from $X = 48$ feet to $X = 50$ feet. When **VLIM** is treated as a lower bound (minimum) the program searches out from each side of the cell over the 10 foot search range shown in the figure. If a velocity above the minimum threshold is found within the search range on either side of the cell, the habitat for that cell is included in the total habitat calculated for the study site. Here, a velocity slightly above the threshold is found 8 feet from the right side of the cell (at $X = 58$ feet) and a velocity of nearly 3 fps (feet per second) is found exactly 10 feet from the cell (at $X = 60$ feet). Thus, the habitat value for $X = 48$ feet is included in the conditional habitat total. None of the habitat to the left of $X = 48$ feet was included in the site total because no velocities satisfying the criteria of exceeding **VLIM** were found within 10 feet of those cells. What will be the last cell on the right to be included in the conditional habitat total?

Table 4-4 contains the cell velocities for cross section 0.0 at 139 cfs and the values found in the **Habitat Results** table of the **/Models/Habtae** window. Note that the first cell counting from the left bank ($X = 0.0$) where the adjacent velocity weight (**Ad Vel**) becomes 1 is at $X = 48$, and the last cell is at $X = 82$. Also note that the velocity 2.72 fps is the first velocity above the threshold value and is located 8 feet from the right side of cell 48 50.

This table illustrates the case where VLIM is used as a lower bound (minimum threshold) and the sought-after velocity is greater than VLIM. If VLIM was used as an upper bound (maximum threshold), which cells would be, included in the adjacent velocity conditioned habitat and which would not? That is, within the search distance, which cells are within 10 feet of velocities less than VLIM? Use Figure 4-11 and Table 4-4 to determine the answer.

Evaluating HABTAE Results

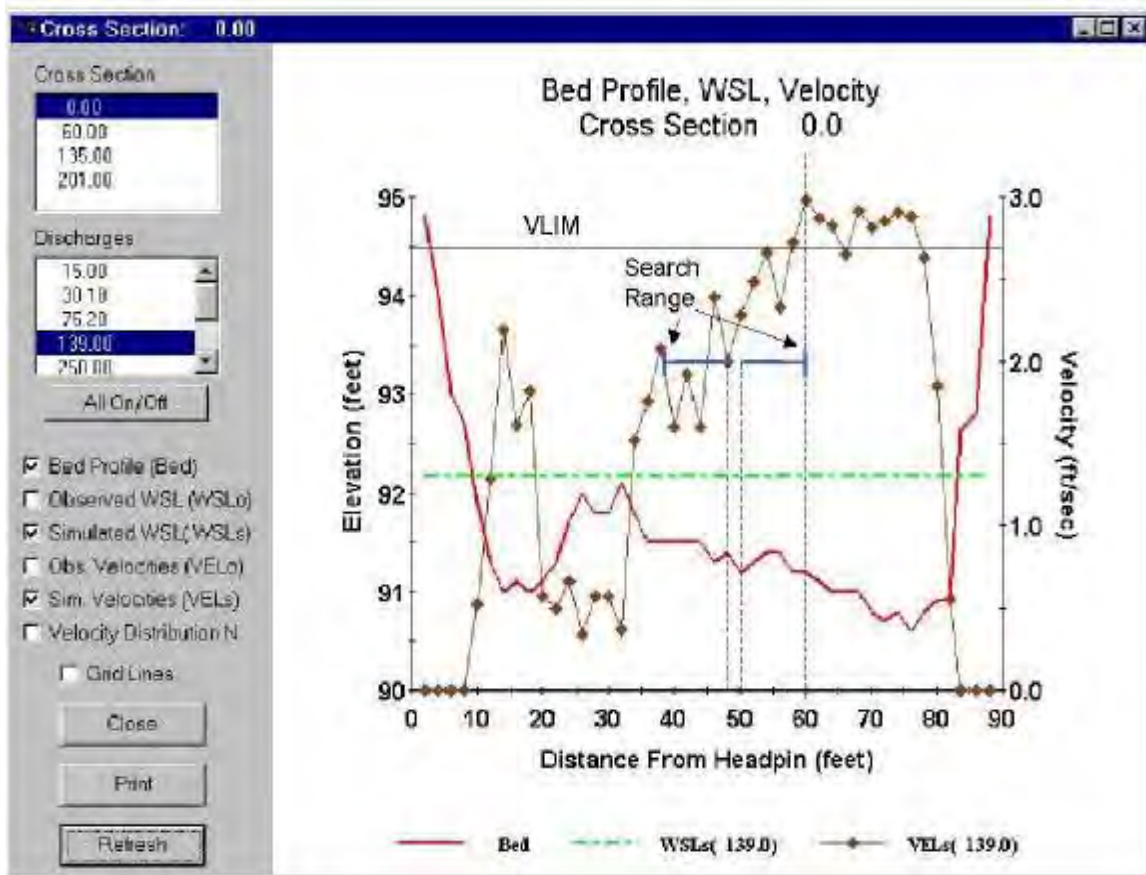
HABTAE program results are accessed on two tabs within the **/Models/HABTAE** window. The **../Habitat Results** tab displays the composite suitability for each wet cell and the **../Zhaqf Results** tab displays the WUA versus discharge relation produced by HABTAE.

In the **../Habitat Results** tab, the user may select the species/life stage, transect, and discharge to display. This allows evaluation of precisely which part of the stream is supplying habitat to each life stage of each species used in the analysis. The **Graph** button in this tab displays a plan view plot of the suitability for the study site. This plot has several interactive selections to display the life stage, discharge, form of habitat output or suitability displayed, etc. Users are encouraged to try all options in this plot to determine which selection best illustrates the habitat feature they wish to display or include in a report. Click the **Refresh** button after making any changes in the plot parameters. A **Print** button is supplied so color copies of the plots can be produced for inclusion in reports.

The **../Zhaqf Results** tab contains the results of the WUA calculation. A plot of WUA versus discharge may be viewed by clicking the **Graph** button. This plot also provides the ability to select the species and life stage(s) to be displayed.

The WUA versus discharge relations produced by HABTAE are the typical output from PHABSIM that are used in instream flow analyses. In many applications, users have ended the analysis at this stage. In an unfortunate number of cases, the discharge producing the highest habitat value has been selected as the recommended instream flow. Such a choice neglects to deal with the feasibility, effectiveness or frequency of occurrence of that flow value. Thus, MESC strongly recommends that users apply PHABSIM in the context of an IFIM study. It is particularly important that habitat time series analysis be performed using the WUA versus discharge relation as a starting point. See Bovee, et al., (1998) for a full development of the IFIM process and how to create and analyze habitat time series.

Figure 4-11. Illustration of adjacent velocity calculation.



Running HABTAE

The HABTAE program may be executed by selecting the desired calculation and output options in the various option tabs and clicking the **Run** button in the **Output Options** tab.

Lateral Migration Analysis using the HABTAM Program

The HABTAM program simulates conditions in which fish can migrate laterally within a cross section in order to make use of the available WUA when there is a change in discharge. Note with the revision of cell definition from DOS PHABSIM, the values of hydraulic characteristics (depth, velocity, and channel index) for each cell are the values of the velocity, depth, and channel index at the right vertical looking upstream.

The HABTAM program calculates WUA at each designated flow using the user supplied suitability curve functions for velocity, depth, and channel index and/or other hydraulic properties within each computational cell derived from the VELSIM program. HABTAM assumes that the available WUA at the user-designated starting flow is fully used and then, based on the user-designated maximum allowable migration distance for each life stage of each species, the program calculates how much of the available WUA at the user-designated ending flow can be used. Fish are permitted to migrate only laterally from cell to cell within a cross section.

Table 4-4. Cell-by-cell adjacent velocity calculations.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Distributed Parameter Models

Effective Habitat Analysis in PHABSIM

Interpreting PHABSIM and Completing the IFIM Process

Use of the PHABSIM for Windows Menu System

PHABSIM for Windows File Structure

Analysis Limits in PHABSIM for Windows

Summary of Chapter 1

Chapter 2, Hydraulic Modeling in PHABSIM

25

Objectives

Laboratories

Introduction

Terms and Definitions of Open-Channel Flow

The user designates a starting flow, ending flow, and a maximum allowable migration distance for each life stage of each species in the right-hand table of the **/Models/HABTAM/Options** tab. The program looks only at the user-designated starting and ending flows for the migration calculations, and processes each cross section as a separate entity, that is, fish cannot migrate from one cross section to another. Assuming that the stream is saturated with fish at the starting flow (all WUA is occupied) and that the flow is then changed to the ending flow, the program permits the fish to migrate in either direction within the cross section up to the maximum allowable migration distance for the particular life stage. The program then calculates how much (the maximum amount) of the WUA available at the ending flow can be used by the fish presently existing in the stream. The results will show that either all the available WUA at the ending flow can be used, or there is an excess of WUA available at the ending flow, which cannot be used because there are not enough fish to use it.

The following assumptions are made for the migration calculations:

1. Fish migration is assumed to begin at the cell boundaries. Thus, when a fish is given a maximum allowable migration distance greater than zero, it is automatically permitted to migrate to adjacent cells. Any distance it might have to travel within its cell of origin is ignored.
2. In situations where the maximum allowable migration distance places a fish exactly on the border of two cells the fish is NOT permitted access to the further cell.
3. Since HABTAM calculates a cell width for each new flow it processes, the width calculated at the flow designated as the ending flow is used as the cell width for the migration calculation. Cell widths change with wetting and drying of the extreme edge cells.
4. When a portion of a cell becomes dry at the user-designated ending flow, the fish are not permitted to migrate beyond the dry boundary point.
5. When a given life stage does not or cannot migrate at all, a value of 0.0 should be entered as the maximum allowable migration distance for that life stage. When this occurs, the program will select for the WUA with migration, the minimum of the WUA at the starting flow, and WUA at the ending flow.

Input to the HABTAM program is through the **/Models/HABTAM/Options**, **../Computations**, **../Migration**, and **../Velocity Calculations** tabs. The program uses these previously entered data and simulation results: (1) HSC curves of aquatic species or recreational activities created in **/Edit/Suitability**, (2) hydraulic simulation results from the WSL and velocity modeling stages, and (3) study site layout (weighting) values from **/Edit/Cross Sections/Cross Section Data**.

Setting HABTAM Options

The HABTAM program provides the user with a wide array of computational and output listing capabilities. Control of computations and output listings is accomplished through several check boxes and data entry fields in the various tabs in **/Models/HABTAM** as described below.

HABTAM options are summarized in Table 4-5.

Table 4-5. Options in the HABTAM program. Option description Action when set to indicated value, notes

Options tab Write Migration Calculation Details (check box)(IOC 1)	results. Recommend leaving unchecked for most runs.
Options tab Write Cross Section Data (check box)(IOC 2)	Writes cross section data (from /Edit/Cross Sections/Cross Section Data) to ZOUT. This documents PHABSIM runs. Recommend leaving unchecked for most applications.
Options tab Write Flow Related Data (check box) (IOC 3)	Writes flow data for each cross section evaluated at each discharge to ZOUT. This is for each cell that is wet. This recapitulates the VELSIM output. Recommend leaving unchecked using VELSIM output table for documentation of most applications.
Options tab Write Computational Details (check box) (IOC 4)	Writes all the computational details for the weighted usable area calculations to ZOUT. Recommend leaving unchecked except when HABTAM gives unexpected results and further evaluation is needed. Output is voluminous, so limiting the number of life stages is recommended when using this option.
Options tab Write Criteria Curve Coordinates (check box) (IOC 8)	Writes the coordinates of the HSC curves used in HABTAM analysis to ZOUT. Recommend leaving unchecked this box.
Options tab Selected Discharges (input table with check boxes)	This table of discharges used in HABTAM calculations has check boxes to select discharges. Typically, all discharges would be selected. However, for some analyses only a few discharges are needed.
Options tab Flows for Migration Calculations (input table)	This table allows the user to set up to 25 pairs of starting and ending discharges to use for migration calculations. The discharges used may be the same as those in the Selected Discharges table. <u>copy</u> from Selected Discharges and <u>paste</u> to Flows for Migration Calculations to set up values are used.
Computations tab Use Channel Index Values of Zero in WUA Calculations (check box) (IOC 7) Writes details of migration calculations to ZOUT. Use when HABTAM produces unexpected	This defines how channel index values of zero (0) are used. If not checked, channel index values of zero are converted to 1.0 which effectively removes channel index from the calculation. 0.0 CI. When checked, a channel index value of zero is used in the calculation of WUA. Recommend checking.

Table 4-5. Continued. Option description Action when set to indicated value, notes

Computations tab Describe Reach Bends (check box) (IOC 12)

management alternatives.

Computations tab Calculate Habitat as % of Total Area (check box) (IOC 10)

Controls how the calculation of WUA will be made. **Standard calculation** -- $CF = f(v) * g(d) * h(ci)$, where $f(v) * g(d) * h(ci) =$ variable preferences for velocity, depth and channel index. **Geometric Mean** -- $CF = \sqrt[3]{f(v) * g(d) * h(ci)}$. **Lowest Limiting Parameter** -- $CF = \min(f(v), g(d), h(ci))$.

Computations tab Habitat Area Calculation (radio buttons) (IOC 9)

Each HSC identifying number is displayed in the left column of this table. Enter the distance for the species/life stage represented by each HSC.

Migration tab Enter Migration Distance for Each Curve ID (input table)

Enter an HSC curve number and additional migration distance for that species/life stage. This option is useful for evaluating more than one hypothesis about the species' migration capability.

Migration tab Enter up to 25 Additional Migration Distances (input table)

These options act the same as the **Vel Calc** options in HABTAE.

- **Mean column velocity** - Uses standard mean column velocity in habitat calculations.
- **Nose velocity** – Uses the 1/7th power law equation. User supplies nose depth and the calibration parameters entered in the input table below.
- **Nose velocity user defined coefficients** – empirical power law equation coefficients. User supplies the nose depth (D_{nose}) and the calibration parameters entered in the input table below.
- **Nose velocity logarithmic velocity distribution** - logarithmic velocity distribution. User supplies the nose depth and the D_{65} of the bed material are supplied by the user in the input table below.

Velocity Calculations tab Cell Velocity Options (radio buttons) (IOC 14)

These options represent the same choices for scanning as for the **Cell Velocity Options**.

Velocity Calculations tab Scan Adjacent Cells for (radio buttons) (IOC 6)

Allows the length to vary from cell to cell (Variable Cell Length) across the stream (i.e., a bend). Default is to use cells as rectangles in plan view. When checked, program uses cells as trapezoids based on the length multiplied by left and right bank weights. To use this option, left and right bank weighting factors must be entered in **/Edit/Cross Sections**.

Calculates habitat as a % of total area. This output is useful in comparative analyses where different flow pairs are compared for relative impacts of different hydropower flow

Evaluating HABTAM Results

The HABTAM program performs a standard WUA calculation to obtain the cell-by-cell habitat values prior to evaluating migration. Thus, there are three tabs for results. As with the HABTAE model, the **../HABTAM/ Habitat Results** and the **../HABTAM/ZHAQF Results** tabs contain cell-by-cell composite suitability and WUA versus discharge values, respectively. The result tables and graphical displays on these tabs act the same as those for HABTAE.

The **../HABTAM/Migration Results** tab is unique to HABTAM. Here the WUA resulting from the constraints of the migration calculations is displayed as an output table and a rotatable 3-dimensional surface plot of the migration results is displayed. Simply stated, the highest point on the plot shows the discharge pair that produces the highest habitat value and the lower valued combinations are easily visualized. For many situations, large flow changes will produce relatively poor migration habitat values and small flow changes will produce relatively good migration habitat. That is, small changes in flow will produce migration habitat values that are near the WUA values obtained for the lower of the two discharges.

When comparing fluctuating flow regimes such as hydropeaking management alternatives, the analyst must take care to recognize that not only the magnitude of the flow change but the frequency with which it occurs, will be a factor in determining which alternative may have the most impact on the aquatic organisms downstream of the dam.

Running HABTAM

Once all options and starting and ending discharges have been entered for the items covered in Table 4-4, the HABTAM program is run by clicking the **RUN** button on the **../Options** tab. If a minimum set of options have not been selected, the program prompts with warning messages.

Effective Habitat Analysis using the HABEF Program

The HABEF program calculates physical habitat considering conditions at two stream flows and/or for two life stages or species. The program uses habitat results from either HABTAE or HABTAM as the source of species/life stage habitat information for each cell. The basic equation used in HABTAE for weighted usable area in cell *i* (*wuai*), is given by the equation:

$$Wuai = A_i * CS_i \quad (4-19)$$

where: *wuai* = weighted usable area of computational cell *i*

CS_i = combined suitability of computational cell *i*

A_i = area of computational cell *i*

HABEF uses *A_i* and *CS_i* for each computational cell used in the physical habitat simulation performed in HABTAE or HABTAM. The WUA used in HABEF is derived from the normal calculation used in the principal habitat programs and is defined by the equation:

$$WUA = \sum_{i=1}^{ncell} CS_{i,A_i} \quad (4-20)$$

The usable area (UA) can also be computed and is derived from:

$$UA = \sum_{i=1}^{ncell} CS_i A_i$$

(4-21) if $CS \leq 0.001$ then $CS = 1.0$

ii

if $CS < 0.001$ then $CS = 0.0$

ii

The user can select either of these habitat definitions for the computation of effective habitat during execution of the program by specifying the appropriate options within the **/Models/HABEF/Options** tab as explained below.

In addition to these basic calculations, the HABEF program can be used to conduct a number of analyses in which comparisons of available habitat on a spatial basis can be examined between species or life stages pairs.

The basic computational options for the HABEF program are listed below with a description of each option provided in the **/Models/HABEF/Options** tab.

Union Of Life Stage 1 With Life Stage 2 -Use two species/life stage HSC Competition Analysis -Use two species/life stage HSC Stream Flow Variation Analysis (Minimum WUA) -Use one species/life stage HSC Stream Flow Variation Analysis (Maximum WUA) -Use one species/life stage HSC Effective Spawning Analysis -Use two species/life stage HSC Stranding Index Analysis -Use one species/life stage HSC

Union Analysis

The first option in HABEF is the Boolean algebraic union of two life stages or species. The WUA results from HABTAE or HABTAM are compared on a cell-by-cell basis for both selected life stages (species/life stage) at all flows in the data set. This may be the union of two life stages of the same species (i.e., fry and juveniles) or it may be the union of two species/life stages (i.e., rainbow and brown trout adults). A union analysis will usually result in a WUA value for the study site for each given stream flow that is greater than the higher of the two independent variables, but less than the sum of the two.

Competition Analysis

Of considerable interest in habitat analyses is the competition of two life stages or two species for the same space. An analysis of habitat competition can be done using Option 3 in HABEF. Most likely, two species will compete for some of the habitat; yet, in other places have the habitat all to themselves (assuming two species are in the stream). In the areas (cells) where direct competition occurs, there are cells where one species/life stage (1) is better suited than the other life stage (2); and other cells where the converse is true. Option 3 gives information on both of these possibilities. It should be noted that this analysis does not explicitly take into account the behavior of either species.

When this option is selected, HABEF first calculates habitat for species/life stage "1" in cells where habitat for the species/life stage "2" is zero. This is combined with the amount of habitat occurring in computational cells where combined suitability is greater than 0.0 for both species but where species "1" has a higher combined suitability value than species "2". Thus the competition option describes the total WUA for cells where species "1" dominates. The program reports this in the column labeled **WUA 1>2 in 1&2**. The inverse calculation is simultaneously performed for species "2".

In interpreting the results, situations where one species clearly has superior habitat conditions to the other (for example, if **WUA 1>2 in 1&2** is two or more times greater than **WUA 2 in 1&2**) it is likely that behavior alone would not allow the species with the less favorable habitat to out-compete the species with the more favorable habitat. When the habitat areas derived in the competition analysis do not significantly favor one species over the other, another form of analysis outside of PHABSIM may be needed to determine the effects of competition in the study reach.

To run this option, the two species to be evaluated are selected in the two input cells on the **/Models/ HABEF/Options** tab and the **Competition Analysis** radio button is set, followed by clicking the **Run** button. Changing to the **../Results** tab, the user will find that in addition to the standard WUA result (sum of cell area times composite suitability), the following WUA sums are accumulated under the indicated column heading.

WUA (1 and 2) This is a Boolean intersection of all cells where both species have WUA>0. This column contains the sum of the surface area of all cells that have both species with non-zero habitat. That is, as long as both species have more than 0.001 units of habitat, the cell is counted in this sum. This value is an indicator of the total surface area of the stream where competition may occur.

WUA (1 = 2) Intersection: This value is a sum of the WUA for only those cells where the WUA values for both species are equal. This column commonly contains zeros.

WUA (1 in 1&2) This is the sum of cell WUA values for species 1 for all cells where both species 1 and species 2 have habitat values greater than 0.001. (e.g., this is the Species 1 habitat in potential competition areas.)

WUA (2 in 1&2) This column contains the sum of cell WUA for species 2 for all cells where habitat for both species 1 and 2 is greater than 0. This is the species 2 habitat in potential competition areas.

WUA (1>2 in 1&2) This is the sum of WUA for species 1 where species 1 WUA is greater than species 2 WUA in potential competition cells.

WUA (2>1 in 1&2) This sum is the opposite of the above.

Competition analysis is used to compare the results from a WUA analysis for two species at the same stream flows or for the same species/life stage at all combinations of flows supplied in the **Edit/Discharges** menu. Scroll the results table to display all columns. As with other PHABSIM for Windows results, these may be pasted into a spreadsheet.

Stream Flow Variation Analysis

The purpose of the stream flow variation analysis is to look at available habitat at two flows with both sets of flows varying over a range of discharge. Recall that HABEF output contains all combinations of flows contained in the discharge list. The streamflow variation analysis option allows the analyst to evaluate which variation in flow produces the least or most usable area and Weighted Usable Area. To run this option, the same species/life stage (same HSC curve number) is entered in both input cells on the **/Models/ HABEF/ Options** tab and the **Streamflow Variation Analysis** radio button is set. The **../Results** tab contains entries for the sum of usable area, WUA and minimum or maximum WUA as noted below.

Maximum and minimum values for specific discharges can be obtained from the diagonal of the streamflow variation results matrices as the diagonal represents a no-variation case. The minimum and maximum values can be used to compare the state under one condition (flow, species, etc.) for a specific cell to the state with a second condition in the same cell. The **Streamflow Variation Analysis (minimum WUA)** option determines the minimum WUA value compared between each set of discharges for each computational cell, and the **maximum WUA** option does the converse. The summed results represent the aggregate results of those cell-by-cell comparisons.

Effective Spawning Analysis

In effective spawning analysis, an area available for spawning habitat is only included as habitat if suitable conditions continue to exist over the period of incubation. Thus, it may be useful to run this analysis over the range of discharges that are likely to exist during the incubation period. If the lowest discharge that is likely to be encountered is significantly lower than the discharge at which spawning takes place, then a large amount of streambed that was wet at the time of spawning may become dry or freeze during incubation. Such an event may cause the spawned eggs to die.

The results contain all combinations of flows set in the discharge list. The user may wish to select a smaller range when reporting effective spawning results.

When **Effective Spawning Analysis** is selected, the WUA within a computational cell is determined from the relative amount of WUA in the computational cell at the second discharge. If the WUA in the computational cell at the second discharge is greater than the WUA in the computational cell at the first discharge, then the WUA is set to the WUA within the computational cell at the first discharge. If the WUA at the second discharge for the computational cell is 0.0, then the WUA is set to 0.0.

Stranding Index Analysis

When **Stranding Index Analysis** is selected, the program computes an index of the habitat isolated when the flow drops. Basically, the available WUA in a computational cell is determined in the same manner as for effective spawning above. However, the stranding index is then computed according to the equation:

$$\frac{\sum WUA_{\text{effective}}}{\sum WUA_{q1}} \text{ Stranding Index} = (1.0 -) * 100.0 \quad (4-22)$$

$\sum WUA_{\text{effective}}$ = the effective WUA described under Option 7 summed over all computational elements $\sum WUA_{q1}$ = the WUA summed over all computational elements at first discharge

When performing stranding index analysis, users are cautioned to carefully check the output and evaluate only those conditions where the flow is dropping.

Summary of Chapter 4

This chapter presented the wide variety of habitat simulation approaches available in the PHABSIM for Windows software. Using commercial spreadsheet software to aggregate variables in ways that are not explicitly handled in PHABSIM can further enhance some analyses. For example, conditions with and without cover can be aggregated by adding the WUA values for a species/life stage with and without cover to obtain a final habitat – discharge relationship that encompasses both conditions. PHABSIM users are encouraged to adapt the analyses they perform to the problem at hand and not to be limited by the specific processes coded in this software. The next chapter provides some ideas for using PHABSIM in various situations. The ideas and cautions in it are intended as thought provoking examples that can be built upon when using PHABSIM as part of an IFIM-based study.

Chapter 5. Interpretation of PHABSIM within IFIM

Objectives

The objectives of this chapter are to present several approaches to interpreting and using the output from PHABSIM within the context of the Instream Flow Incremental Methodology (IFIM).

Laboratories

No specific laboratory exercises are provided for this material.

Introduction

This chapter presents examples of particular situations and analytical approaches that may occur or be applied within an application of PHABSIM. During the analysis scoping phase of IFIM (see Figure 1-1), the stakeholders involved in an instream flow issue are expected to reach consensus on the type of analysis to be used for the problem, the technology to be applied, and the approaches to interpreting the analytical results. As noted in Chapter 1, an IFIM application may be entirely successful without use of PHABSIM if the issue can best be decided based on criteria other than physical microhabitat. MESC strongly recommends that consensus on these issues (type of analysis, scale of the problem, technology to be used, and interpretation of results) be reached prior to investing time and resources in the study. Doing so has been found to greatly reduce after-the-fact disagreements on methods and interpretations, allowing decision makers to focus on the issue of allocating instream flows.

Once consensus has been reached to use PHABSIM, one of the most challenging aspects in its application is the proper use and interpretation of PHABSIM model results within the IFIM framework. It is important to stress that the basic WUA versus discharge relationships obtained from the habitat modeling process in PHABSIM represent only instantaneous variation of physical habitat with flow and should not be interpreted in the absence of one or more alternative flow regimes for a particular study site. This is why a study employing PHABSIM is not considered to be an IFIM study unless flow and habitat time series including seasonal habitat needs for all life stages are analyzed.

Picking the Peak of WUA Curves

One potential error PHABSIM users commonly make is a “blind” evaluation of the WUA versus discharge function where the instream flow is selected to be the discharge at which the peak (or maximum) WUA value occurs. This can create a number of problems as illustrated by the following example.

In a study, an investigator completed a PHABSIM analysis for a number of target species and life stages. After reviewing the component habitat versus discharge relationships, the investigator selected the most sensitive species and life stage (i.e., habitat in shortest supply) for each month and then recommended an instream flow regime by selecting the flows at the peak of the WUA curve for each month of the year. This seemed a prudent and defensible approach at the time. However, it was found out some time later when the discharge records for the gauge at the study site were examined on a monthly basis, that many of the selected monthly instream flows corresponded to discharges with monthly exceedance values in the ranges between 10–15%. That is, flows greater than or equal to the recommended flows occurred only 10–15% of the time. In essence, the investigator was claiming that near flood flows were necessary for the recommended instream flows in most months. Unfortunately for this particular investigator, no rational biological justification could be offered in defense of the selected flow regime.

This example is provided to highlight the point that failure to evaluate the feasible flow regime(s) at the site during the evaluation of instream flows can lead to problems in negotiating instream flows and is highly discouraged. There are situations, in which flows greater or lesser than the flow associated with the peak of the WUA curve may make rational sense and perhaps the most critical element of the interpretation process is the rational basis or framework for evaluation of model outputs. IFIM emphasizes creation and analysis of habitat time series as a key component in this framework.

For example, the investigator above could examine the monthly flow duration curves and consider where the median monthly flow (i.e., 50% exceedance) or some other exceedance level lies in relationship to the flow at which optimal habitat conditions exist for a target species and life stage. If the median flow was selected for consideration and is higher than the optimal flow, the investigator may consider allowing some level of abstraction down to the flow at which the optimum habitat occurs. If the median monthly flow falls below the flow at which the optimal habitat occurs, then the investigator can examine the magnitude of habitat or percentage reduction and decide if further reductions would potentially represent any level of adverse conditions. In many cases, this type of approach which requires the investigator to consider the consequences of a particular flow regime in light of the amount and or quality of habitat for one or more exceedance ranges is encouraged and permits the consideration of known life history needs that are not directly reflected in the results of the habitat versus flow relationship derived from PHABSIM.

Use of a Most Sensitive Species and Life Stage

In many instream flow studies, a number of species and life stages are considered to be important for evaluation within PHABSIM at an early stage of the project (i.e., scoping). For example, a stream may contain salmon, brown trout, arctic grayling, and dace. After considerable effort in the selection and application of each of these species and associated life stage suitability index curves for representative life stages, the analyst may obtain a family of WUA versus discharge functions as illustrated in Figure 5-1. For some time periods of the year many, if not most, of these species and life stages may be present in the system. Therefore, the investigator is faced with a difficult task of integrating all these curves in a coherent manner to establish a recommended flow regime.

One approach to integrating multiple WUA relationships is to base the instream flow assessment on the single species and life stage that is most sensitive to changes in flow during a critical period. Alternatively, a particular species and life stage may be considered the most important from a management perspective, such as spawning brown trout in a system where the management goal is a self sustaining wild brown trout population. Flows can then be selected based on this single species and life stage while attempting to minimize potential adverse reductions to other species and life stages. In some situations, a reduction in the primary target species and life stage habitat quantity and quality can be made such that other species and life stages can still retain what are considered adequate levels of habitat availability. This approach is sometimes called a “keystone” or “cornerstone” species analysis.

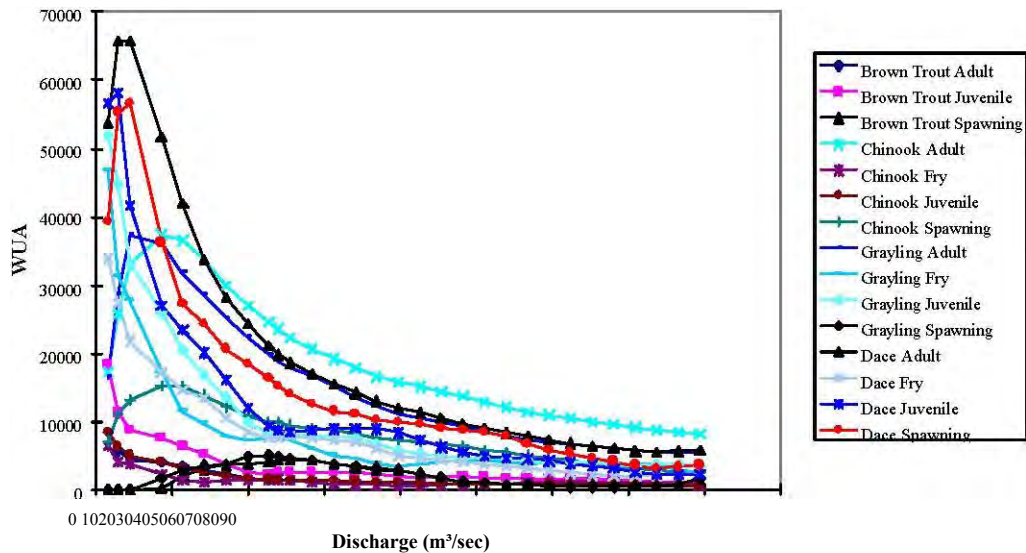


Figure 5-1. Example of WUA vs. discharge relation for a suite of species.

Another approach to the multiple species problem is to apply a two-tiered prioritization process that includes life history stage first, and then species priority. This approach, suggested by Reiser (2001), begins by establishing a list of target species, agreeing on their management priority, and obtaining consensus on the most important life stages of those species at different times of the year. For example spawning habitat may be considered more important than habitat for the adult or juvenile life stages. Then for any given month, if spawning occurs for any of the species, the spawning life stage is given first consideration in the flow analysis. If spawning does not occur for any of the species during that month, go to the next priority life stage for the 1st, 2nd, etc. species and base the flow analysis for that month on that next selected species/life stage. This approach avoids basing the conclusions of the entire analysis on a single “keystone” species. As with all analyses where priorities are established, consensus is vital to avoid conflict after the analysis is complete.

Some applications are not readily amenable to the use of the most sensitive species or critical species and life stage (i.e., they all are the focus of management objectives). In this instance, a post-analysis guiding approach is sometimes possible.

Post-analysis Guiding

A post-analysis guiding approach can take on several forms depending on the context of the project and management objectives. One approach that has been used involves the construction of a community level habitat versus flow relationship. A community habitat curve can be constructed using the original habitat versus discharge relationships or by using a set of normalized habitat versus discharge functions. If normalized habitat functions are to be used, the first step is to re-scale each individual species and life stage WUA versus discharge curve to the maximum value of WUA for each species and life stage (i.e., each curve is re-scaled as a percent of the maximum or optimal habitat) as illustrated in Figure 5-2. The investigator can then combine these curves (or the original unscaled curves) using a weighted arithmetic average to produce a single curve as illustrated in Figure 5-3. The relative weighting factors for a specific critical period for each species and life stage can be selected to represent the management objectives for the system and should be defined during the project-scoping portion of an IFIM analysis.

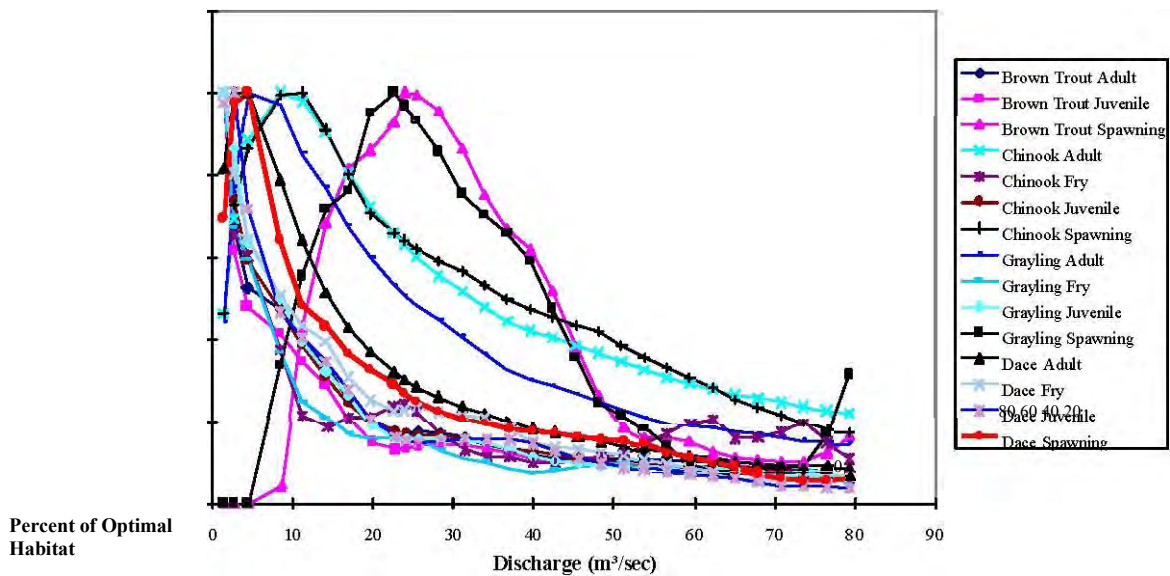
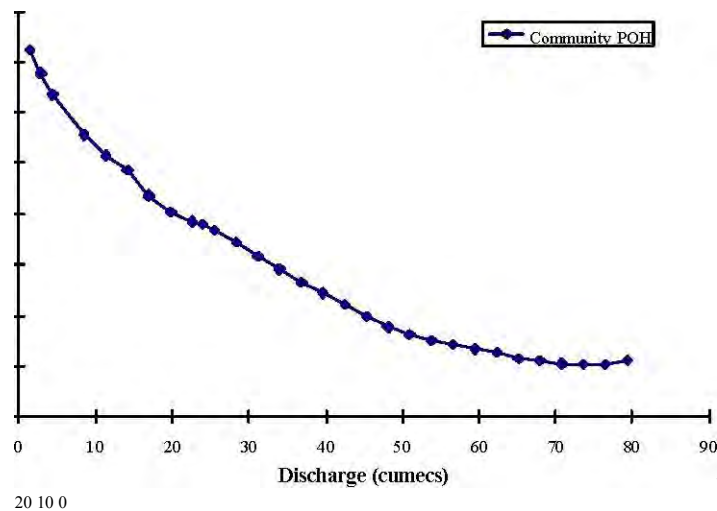


Figure 5-2.

WUA

Normalized
multiple-species
relationships.

Figure 5-3. Combined
versus discharge
% Optimal WUA



community WUA
relationship.

In the analysis scoping stage of IFIM, the stakeholders may choose to develop a community curve for specific periods of the year based on the unique combinations of species and life stages identified by the species periodicity table as discussed previously. It is also possible that the relative weighting factors used to construct the community curves may change between time periods to reflect the relative importance or sensitivity of specific species and life stages during a particular time period. For example, an endangered species may receive a weight of 2.0, while all other species and life stages may receive a weight of 1.0, or spawning may be weighted more than fry during the spawning period. The community curves can be used in subsequent evaluations such as time series and habitat duration analyses. It is strongly advised that individual species and life stage habitat relationships be checked to ensure flow regimes selected provide consistency in the results.

Alternatively, parties to an IFIM application may choose to simplify multiple habitat curves to eliminate very similar or “redundant” WUA versus discharge relationships. In this approach, curves that have the same basic magnitude and functional relationship can either be eliminated or averaged to generate a single curve which in essence represents the guild of species and life stages with similar fundamental relationships between habitat and flow. In some instances, this combining or guilding can be accomplished using normalized habitat functions since many applications focus on relative changes in habitat and not necessarily on the actual magnitude of the habitat change. Similarity in the functional relationships between habitat and discharge for different species and life stages in fact is not uncommon and in a sense is to be expected. For example, fry and juvenile curves for many salmonids actually exhibit very similar habitat requirements, which follow known obligate habitat use for these early life stages. It is also not uncommon for different life stages for different species to use similar habitats. This is reflected in similar HSC curves and thus, similar habitat versus discharge relationships.

The final set of guilded habitat functions can then be used to construct a community level curve as described above, or the most sensitive guild within a critical period may be selected for consideration in further analyses. As mentioned previously, in all cases, habitat-discharge relationships must be evaluated using analysis of habitat time series for feasibility, effectiveness, cost, and risk of failure. The reader is referred to Bovee, et al., (1998) for further development of habitat time series analysis.

Consideration of Quantity Versus Quality

As discussed in Chapter 4, the basic habitat versus discharge relationship represents an aggregation of the component cell WUA values across all cells at a specific discharge for a given species and life stage. Therefore, the results presented in a habitat-discharge relationship such as Figure 5-1 cannot be directly used to ascertain the difference between a total magnitude of WUA which is represented by all cells having a low suitability, versus a WUA result where a few cells contain high suitability values. For example, a stream may have a total surface area of 100 square feet at a given discharge that is composed of 10 equal area cells (i.e., each cell is 10 square feet). A computed total WUA could be derived from all 10 cells each having a combined suitability of 0.1, giving $(0.1)(10 \text{ ft}^2)(10 \text{ cells}) = 10 \text{ ft}^2$ of WUA. Alternatively, nine of the habitat cells could have a combined suitability of 0.0, while the one remaining habitat cell could have a combined suitability of 1.0 giving $[(0.0)(10 \text{ ft}^2)(9 \text{ cells}) + (1.0)(10 \text{ ft}^2)(1 \text{ cell})] = 10 \text{ ft}^2$ of WUA. Fortunately, PHABSIM includes options to exclude poor quality habitat (see **Minimum Effective Composite Suitability Factor (CFMIN)** in Chapter 4). This is illustrated in Figure 5-4 for composite suitability greater than 0.75 for adult brown trout. As can be seen, the peak of the total WUA curve does not always correspond with the peak of highly suitable habitat conditions. The investigator should carefully consider the biological implications of selecting flows that maximize total WUA versus the consideration of an alternative flow that may maximize the area associated with high quality habitat. It should be remembered that all the techniques described above could be used with high quality habitat versus flow functions in a manner equivalent to using the total WUA curves.

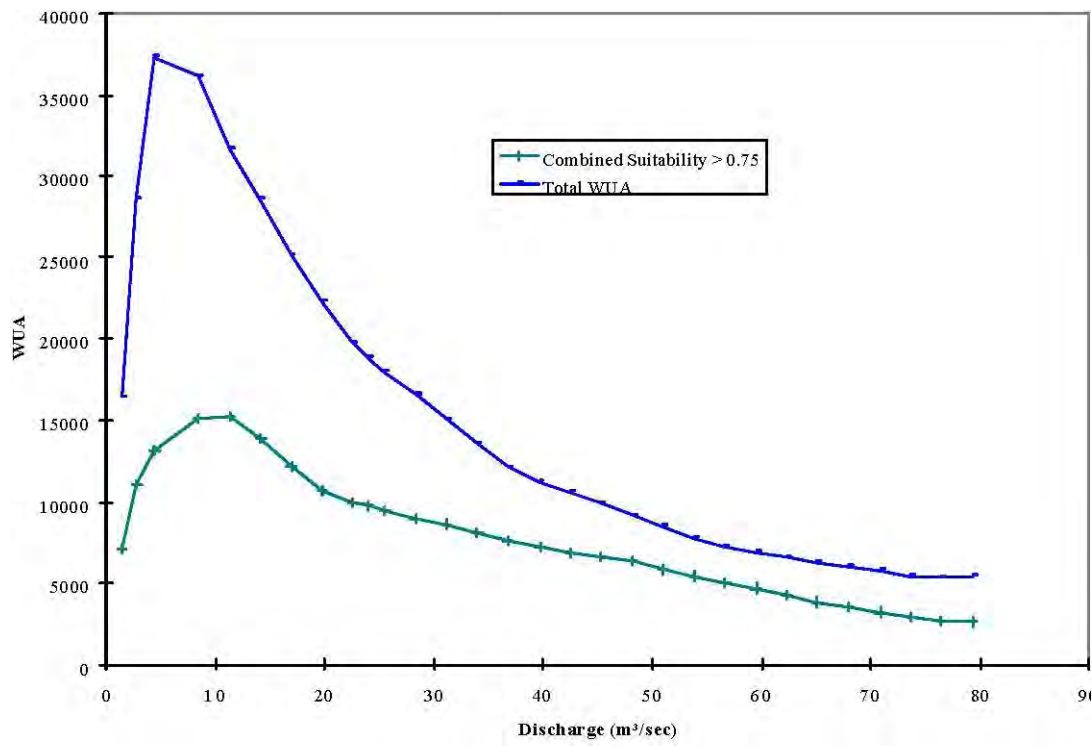


Figure 5-4. WUA vs. discharge for cells with composite suitability > 0.75.

0

Evaluation of Mesohabitat-specific Conditions

HABTAE can be used to generate output on a cross section by cross section basis, or for a group of cross sections by selecting pools only versus selecting riffle habitats. Using this sub-sampling approach, the investigator can develop habitat versus flow functions for specific species and life stages on a mesohabitat basis as illustrated in Figure 5-5. This type of analysis can focus the investigation on species and life stage specific sensitivity to particular habitat types that may be important during critical periods of the year. For example, an analysis may focus on riffle type habitats during the spawning season in lieu of other less sensitive life stages and mesohabitats using this approach. This type of analysis can also facilitate the aggregation of mesohabitat versus flow functions into composite WUA versus flow functions when the proportion of habitat types may change as a function of discharge, or where a gross evaluation of habitat improvement works is desired. Such aggregation can easily be accomplished by exporting PHABSIM for Windows results to a spreadsheet.

Evaluation of Habitat Suitability Criteria

Habitat suitability criteria (HSC) have been an area of considerable controversy in PHABSIM applications since its inception. Recognizing that site-specific HSC may best reflect the habitat utilization of aquatic species, MESC has recommended that either local HSC be developed for PHABSIM applications or that the stakeholders agree on the HSC to be used as part of the analysis scoping process in IFIM.

Adult Trout in Chalk Streams

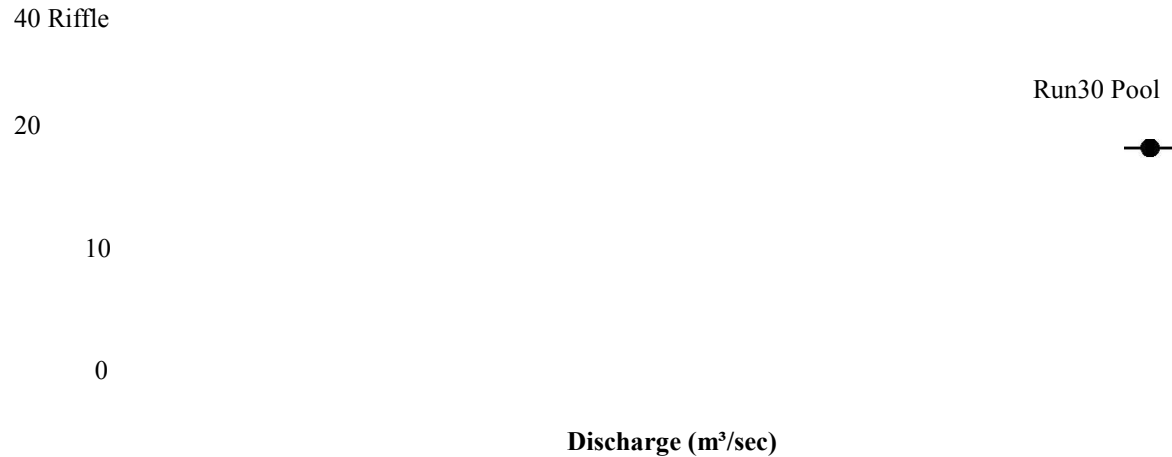


Figure 5-5. Habitat-discharge relationships for mesohabitat types.

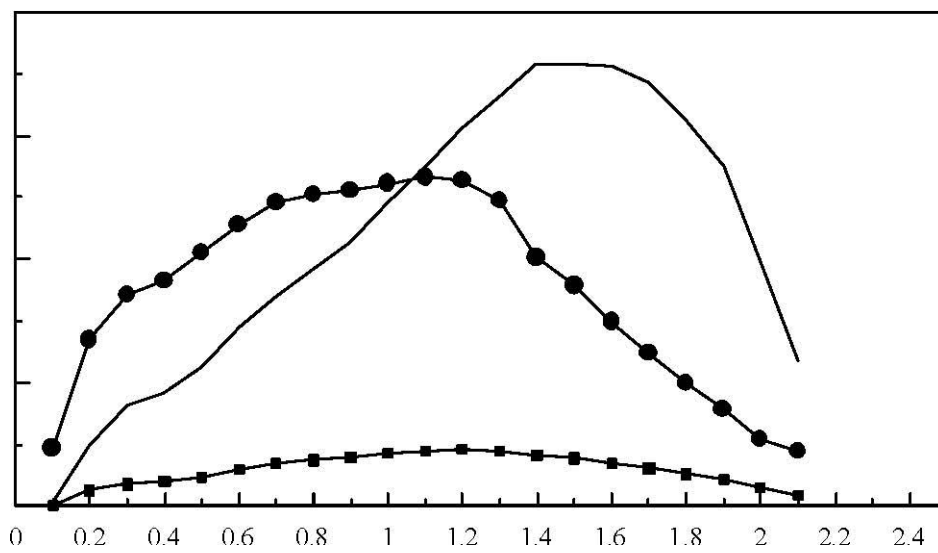
HSC adopted from the literature or other studies may be evaluated for applicability to the study at hand as shown in this example. The investigator may select a cross section at a specific location in the stream where a known habitat activity, such as spawning, was observed. In this instance, the investigator can examine the spatial distribution of combined suitability values across the cross section to determine if the suitability curves correctly demonstrate suitable habitat conditions at the location of known spawning redds as illustrated in Figure 5-6. Prediction of low combined suitability at the known redd location should cause some concern. A more detailed evaluation of the hydraulic simulations (primarily velocity or channel index) in conjunction with a re-assessment of the suitability curves should be undertaken to ensure the habitat conditions are being properly represented.

Decomposition of Single Parameter Suitability

In some streams, one or another of the physical habitat parameters may be the source of greatest change in habitat magnitude with a change in flow. An investigator may find that determining which specific suitability factor is contributing to the estimate of total WUA is important. This can be accomplished, for example, by modifying the suitability curves such that only a single parameter such as velocity is retained, while both depth and channel index are set to a 1.0 for all values. This type of analysis can reveal whether depth, velocity or channel index is the controlling factor over specific ranges of discharges as illustrated in Figure 5-7. Note the relative insensitivity to substrate, but great sensitivity to velocity in this example. In addition, when combined with an analysis of mesohabitat, this type of assessment can lend insight to the physical basis for habitat-specific sensitivity to flow for a critical life stage in the target stream.

% Available Habitat

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4



Distance from
R.H. marker (m)

Spatial Niche Analysis

Although not commonly recognized, PHABSIM can also be used to examine the spatial niche of a stream as a function of discharge in terms of depth, velocity, or in some circumstances, channel index. An investigator may find that HSC

C.S.I.

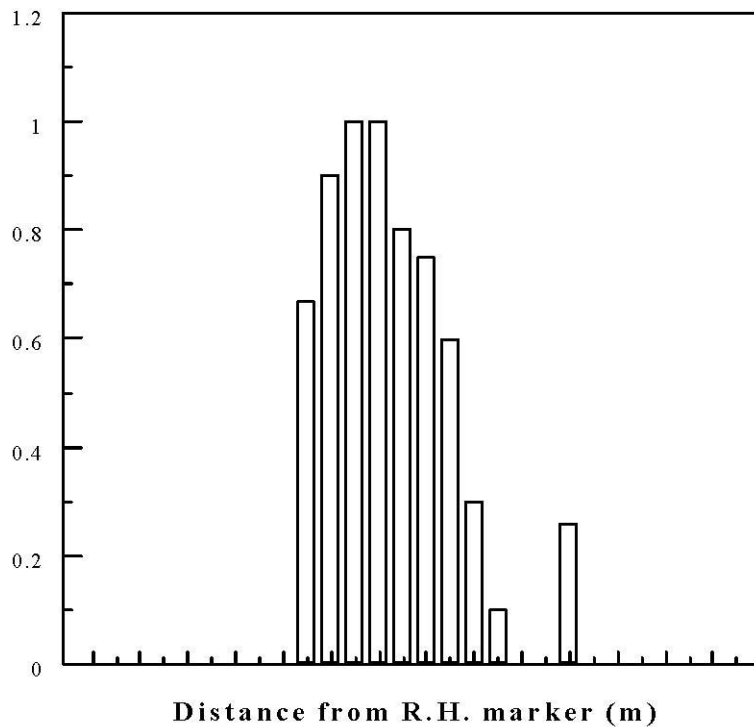


Figure 5-6. Distribution of spawning suitability on a selected cross section.

curves are not readily available, or may simply wish to examine the flow dependent characteristics of spatial niches as part of the overall study. In this type of approach, a fish community may be partitioned by species and life stages into a simple spatial matrix representing habitat use along a gradient of depth and velocity as illustrated in Table 5-1. Note that in this type of analysis, no species or life stage HSC curves are necessary since only a community level habitat (i.e., spatial niche) partitioning is used. Suitability curves, which define usable habitat as 1.0 over each combination of depth and velocity can be used to compute the area, associated with each spatial niche at each discharge. These relationships can then be aggregated to construct a cumulative area versus discharge relationship as illustrated in Figure 5-8. In this figure, each line represents the component area that each spatial niche in Table 5-1 contributes to the total surface area of the stream at a specific discharge.

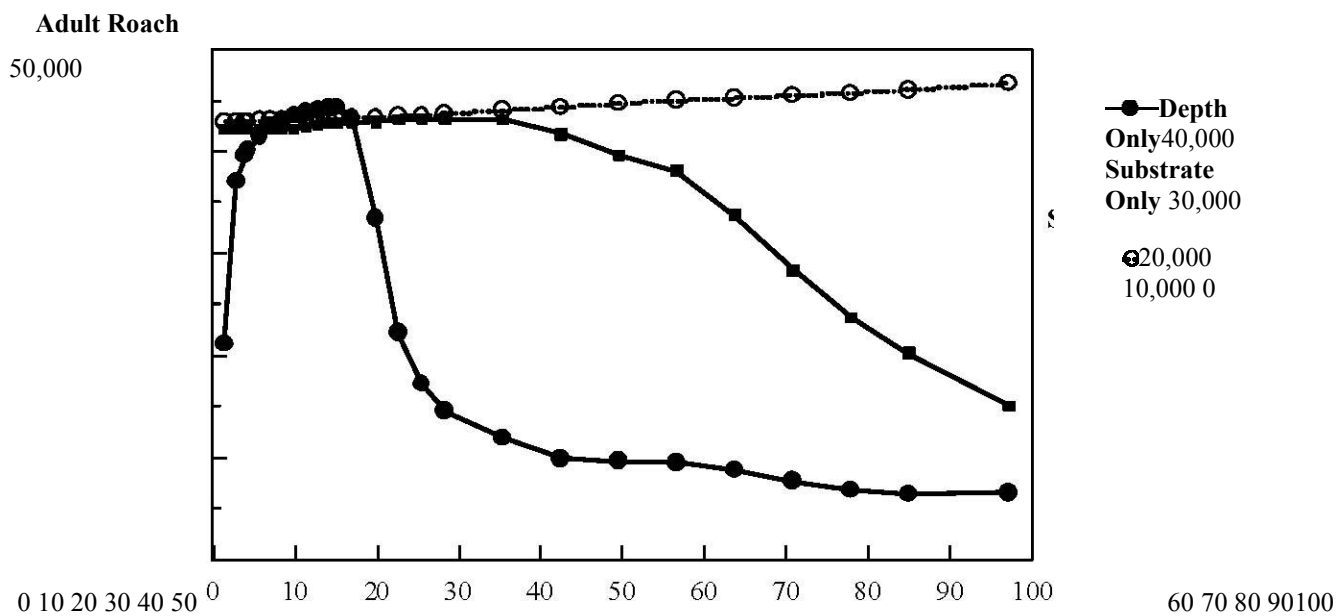


Figure 5-7. Single parameter habitat-discharge

relationships.

Table 5-1. Example of a hypothetical spatial niche indicating component habitat partitioning by resident species/life stages.

WUA (m²/1000m)

Depth gradient (m)

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

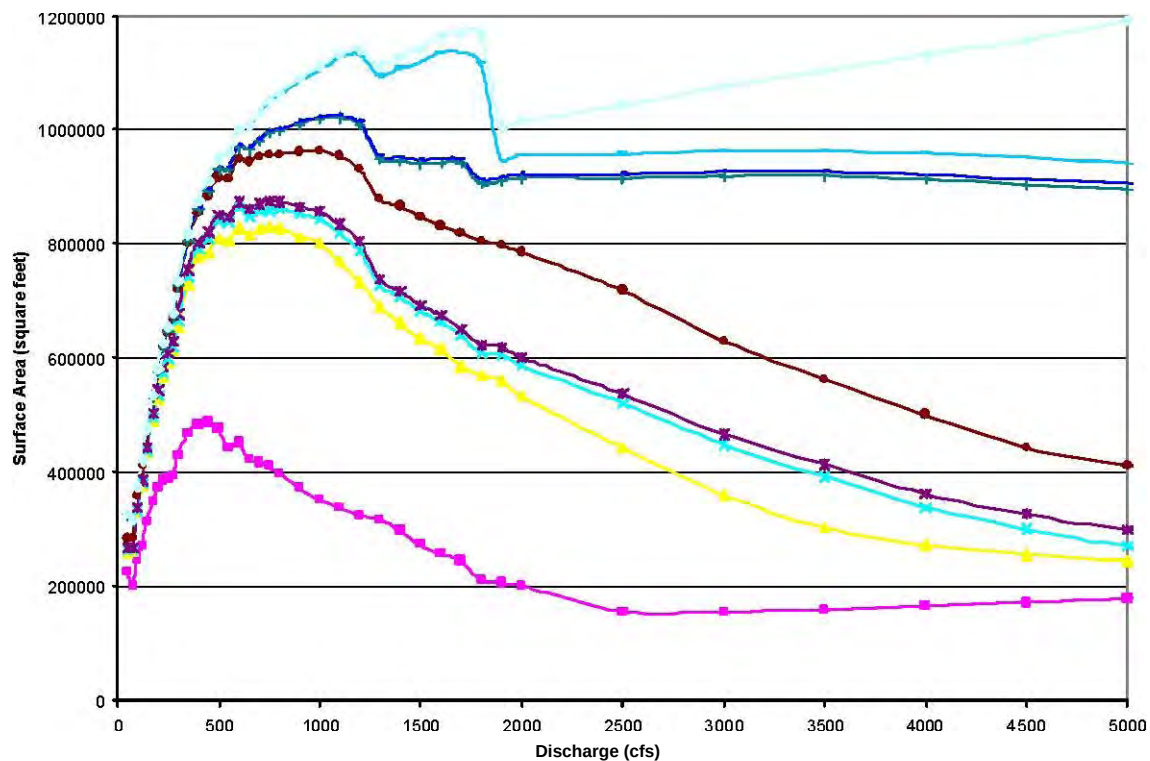


Figure 5-8. Example of spatial niche composition versus discharge, each line represents one item in Table 5-1.

It is also possible to use these results to compute a variety of ecologically-based indices such as a diversity index. The diversity index can be computed using the available habitat areas at each flow to produce a habitat diversity versus discharge relationship. The analyst can then examine these relationships in light of specific discharges and the associated amounts of specific areas represented by specific habitat niches or overall habitat diversity. This may lead an investigator to select a discharge or discharge range, which either maximizes the spatial niche of a particular community element(s) or favors a broader range of diversity of available habitats.

Habitat Time Series

While not explicitly included in the PHABSIM for Windows software, habitat time series analysis is a key part of an application of IFIM. Because of its importance in IFIM and relationship to PHABSIM results, the following discussion of habitat time series is included in this document. All other factors being equal, it is a reasonable assumption that current populations of fish are dependent on the antecedent history of habitat availability. It is also logical to assume that future population levels will be influenced by the time dependent characteristics of habitat availability. In many instances, it is the time dependent characteristics of habitat occurrence that ultimately may limit a particular life stage and, therefore, control the fishery population. This has often been referred to as a limiting life stage or population bottleneck. An instream flow assessment based on PHABSIM can be used to explore these potential limiting conditions for specific species and life stages through the application of habitat time series. This extension of the basic PHABSIM model results (the weighted usable area versus discharge curve) to temporal predictions of habitat can be a crucial step in the examination of habitat availability that may influence long-term changes in fish and invertebrate populations. Use of habitat time series in an IFIM analysis is more extensively covered in Bovee, et al., (1998). Habitat time series may be generated using programs in the TSLIB (Time Series LIBrary) group of programs or through use of spreadsheets.

To conduct a habitat time series analysis, the user needs to derive the basic habitat versus flow relationships for target species and life stages and also obtain a baseline and various alternative time series of flow(s) at the study site. The major premise of habitat time series analysis is that habitat is a function of stream flow and that stream flow varies over time. The basic steps to calculate a habitat time series are illustrated in Figure 5-9, where the habitat versus flow function (i.e., WUA vs. discharge) is integrated with the flow at each time step to derive habitat availability at each time step. The habitat time series can then be analyzed to derive a habitat duration curve similar to flow duration curves derived in hydrologic analyses as illustrated in Figure 5-10 and discussed below.

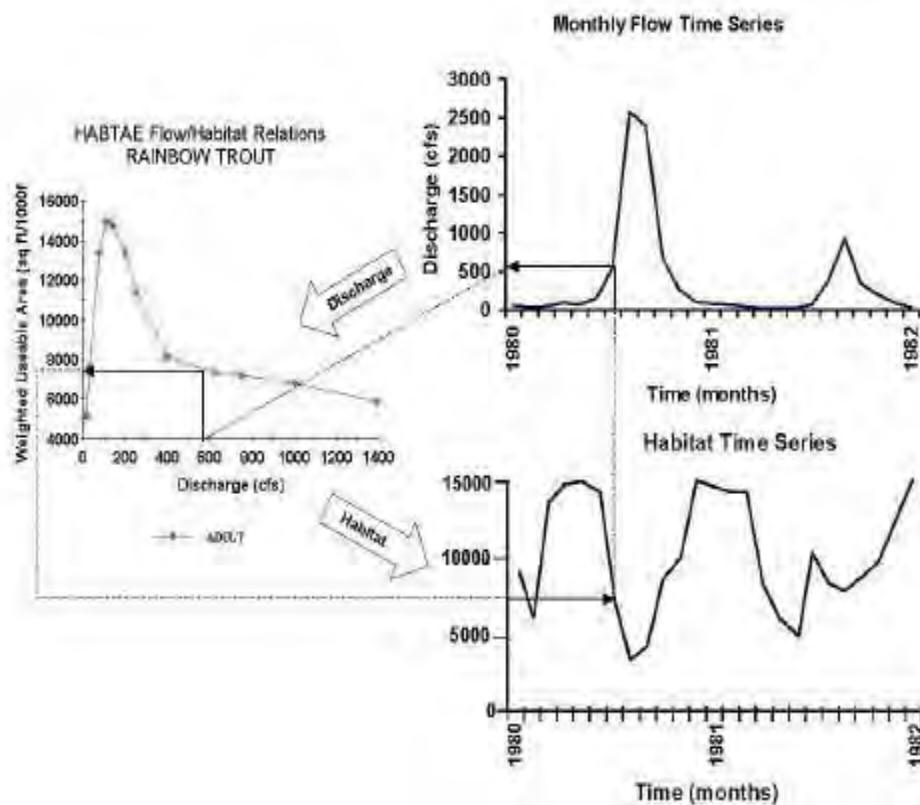


Figure 5-9. Generation of a habitat time series.

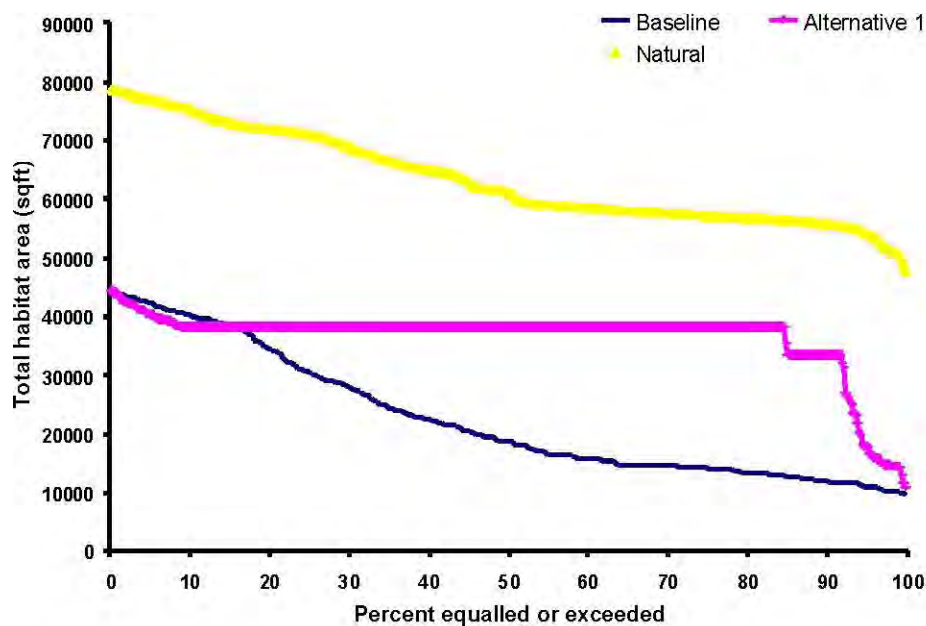


Figure 5-10. Example of habitat duration curves derived from three habitat time series.

In its various forms, time series analysis provides a very valuable method of assessing the impacts of changes in flow regime. The most common approach to this is to generate habitat time series data for a study site both under baseline conditions agreed upon in the analysis scoping phase of IFIM. The flow time series used must incorporate the effects of an abstraction or other alternative flow management regime as illustrated in Figure 5-10. It may also be appropriate to produce habitat time series to show the effects of different levels of human manipulation of the stream. Analysis of these alternatives can take a variety of forms. The following are some of the more common approaches:

1. A simple comparison of the two (or more) sets of habitat time series data can identify periods where the human influence has greater/lesser impacts.
2. Using the above data, the percentage reduction in habitat can be calculated, again to assist in the identification of periods of greater/lesser impacts. (See Bovee, et al., 1998)
3. Mean monthly (or other time interval) habitat levels and mean monthly percentage habitat losses can be calculated to examine more general patterns of habitat change.
4. A combination of these analyses can be used to identify which of the alternative flow regimes being analyzed minimizes potential adverse impacts or provides habitat improvements for critical time periods or life stages to meet habitat management objectives.

Once the habitat time series data sets have been calculated, the user may wish to aggregate values at some appropriate time interval such as using daily time steps aggregated to monthly, seasonal, or even yearly intervals, in order to examine habitat changes on a different time interval basis. Commonly used summary statistics of habitat time series for any interval of time include:

Mean habitat Median habitat Minimum habitat Maximum/optimum habitat Index-A: mean of all the habitats between 50% and 90% exceedence, i.e., the majority of the low flow events Index-B: mean of all habitats between 10% and 90% exceedence An exceedence statistic e.g., 90, 95-percentile habitat Number of days below a habitat quantity threshold, or total threshold deficit

Bovee, et al. (1998) contains a full discussion of these indices and their use in negotiating instream flow regimes.

Habitat Duration Curves

Further analysis of habitat time series may be achieved using a variety of techniques developed for river flow analysis. The first example of this is the habitat duration curve (Figure 5-10). A duration curve, whether for flow, habitat, or another instream variable, displays the relationship between the variable and the percentage of time it is exceeded. Duration curves are constructed by sorting the data (time series of flows or habitat values) from highest to lowest, and expressing each data point as a percentage of the total number of values. These methods are of particular use in the analysis of how alternative flow regimes affect habitat available to individual life stages of a species.

Duration curves are particularly useful for assessing the impacts of alternative flow regimes over the complete range of discharges considered for alternative flow scenarios as shown in Figure 5-10 which gives “baseline” (with habitat reduced by an abstraction), “alternative” (a proposed managed flow regime) and “natural” (with natural levels of habitat) duration curves. They are also useful for examining habitat changes due to artificial influences for the time periods identified as critical in the species/life stage periodicity analysis or on a seasonal basis by simply sampling from the appropriate portions of the time series to build the habitat duration curve. It is important to note that the habitat duration curves can only be interpreted as representing the amount of time that a particular magnitude of habitat is equaled or exceeded. Other forms of analysis discussed below must be used if the investigator is interested in determining the amount of time that habitat is continuously below some threshold. In other words, a monthly habitat duration curve may indicate that a given quantity of habitat is equaled or exceeded 90% of the time, but one cannot determine from the flow duration curve if the lowest 10% of habitat availability occurs once every fifth day or for five continuous days. From a biological perspective, differentiation between these two cases may be of critical importance in understanding limiting habitat conditions such as chronic versus acute episodes.

Habitat Duration Threshold Analyses

This technique has been used to characterize periods of flow below a certain threshold habitat value. In a PHABSIM study, it allows the user to assess not only the number of low habitat events but also the duration (length of time) of each low habitat event. For example, habitat may drop below a threshold level for 20 separate days in a year, or it may drop below the same level for a single continuous period of 20 days within a year. These two scenarios would appear the same when plotted on a duration curve but may have very different implications for the target species/life stage in question. In this type of analysis, within an IFIM study, a habitat threshold level must be set by the investigator and the relative importance of both the number and length (i.e., number of time steps) over which habitat is at or below this threshold must be interpreted using the available knowledge of the target species/life stage in question. An example of this technique illustrating the use of habitat duration threshold analysis is presented in Capra et al. (1995).

Choice of Flow Time Series and Baseline Conditions

In the initial planning stages of an IFIM study using PHABSIM, an important consideration will have been the sources of flow data that are available. When changes in flow regime are to be considered, predictions of historical physical habitat are commonly compared with alternative modeled scenarios that could have occurred over the same historical time period, including the “naturalized” condition. This often requires the development of models to predict the flow regime in the river concerned under the “naturalized” flow conditions, which in itself can form a major part of a study. Some key factors in selecting flow data for use in habitat time series analysis are that the flow data is on a time step appropriate for the issues and target species/life stages in question (e.g., 15 minute flow values may be essential for analysis of the impacts of hydropower schemes), that the flow time series is sufficiently long to allow the production of robust seasonal habitat duration curves and other time-based statistics, and that modeled flow scenarios properly represent anticipated management influences, naturalized flows, or other factors as appropriate.

With regard to periods of record, there are no set guidelines. Each study should be considered on a case-by-case basis. However, if daily flows are available, it is suggested that at least 10 years of flow data be used. If the study is using monthly flow data, then 15 or more years may be required. Shorter or longer time periods may be appropriate, however, given data availability and study objectives.

Some Important Factors in Time Series and Duration Curve Analysis

It is important to note that a habitat duration curve shows exceedence percentiles for values of habitat, ranked from highest to lowest. It does not simply show flow exceedence percentiles mapped to their corresponding habitat values. It is also important to note that there is generally not a continuous increasing relationship between habitat and flow in a habitat versus flow function for a target species/life stage. Instead, habitat often increases with flow up to a maximum at a certain flow, and then habitat values decrease with increasing flow. This phenomenon may result in some portion of the habitat duration curve representing levels of habitat produced under both high and low flow conditions. This is unlike a flow duration curve, where high flows are always associated with low exceedence values. As a result care must be taken when interpreting habitat duration curves a low habitat availability does not always result from a low flow.

While not detracting from the use of habitat duration curves in the evaluation of the impacts of alternate flow regimes, caution should be exercised in their interpretation. It is possible to overcome these issues by plotting values of flow alongside habitat duration curves so that the analyst can see which flows are producing a given habitat exceedence level. Alternatively, the analyst may confine the period of analysis either by restricting it to certain time periods of the year, when flows are lowest, or simply by not calculating habitat exceedence percentiles for flows above the peak in the WUA versus discharge curve. It should also be remembered that duration curves do not give information about the temporal distribution of low flow or habitat events, i.e., whether they occur together or separately. Other techniques such as a habitat/flow threshold analysis, as outlined above, should be considered for this purpose.

Integration of Channel Maintenance and Sediment Transport

One of the more important aspects of an ecologically sound flow regime is the recognition that the long-term ecological function of a stream or river corridor requires that the physical processes that form and maintain a channel must be protected. There are numerous examples where sediment transport has been either severely reduced, such as below a dam, or significantly increased, such as runoff from a watershed that has been intensively mined or burned in a forest fire. In these situations, the channel will react to the change in the sediment dynamics and either degrade or aggrade differentially along its longitudinal gradient. In some instances, a well-defined river channel will become highly braided, in other circumstances the opposite effect has been observed. This problem, of course, is not confined solely to changes in the sediment supply since alterations in the flow regime, such as seasonally maintained low flows or abstraction of the high flow component for reservoir storage, can result in changes to the dynamic equilibrium between the flow and sediment transport. This can, in turn, result in changes to channel structure and habitat composition as well as changes in the dynamics of the streamside or riparian vegetation.

PHABSIM for Windows does not contain models of sediment dynamics. To include sediment issues in an IFIM application, other models and expertise must be brought to the problem. Appendix 4 contains a brief discussion of some of the issues to consider when including channel maintenance in an instream flow analysis.

Summary of Chapter 5

This chapter covered numerous ideas for application of PHABSIM to various analysis situations. These items are intended as thought provoking examples to encourage PHABSIM users to adapt the analysis to the situations they may encounter in practice. This section concludes the PHABSIM for Windows user's manual.

Appendix 1. Glossary of Terms and Program Names

Terminology

The following terms and their definitions are provided to help the reader understand some of the specialized vocabulary utilized throughout PHABSIM in the description of open channel hydraulics, suitability curves, and habitat modeling.

AREA, CONVEYANCE: Cross-sectional area of a stream perpendicular to the flow.

AREA, CROSS-SECTIONAL: The area of the cross section containing water, perpendicular to the direction of flow. (Units: square feet or square meters).

AREA, USABLE: The surface area of a stream that can be used by an aquatic organism. (Units: square feet or square meters).

AREA, WEIGHTED USABLE (WUA): The surface area of a stream weighted by its suitability to an aquatic organism. (Units: square feet or square meters).

AREA, WEIGHTED USABLE BED (WUBA): The bed area of a stream weighted by its suitability to an aquatic organism. (Units: square feet or square meters).

BACKWATER: (1) A region of a stream where the water surface level is governed by a downstream control (Hence the term step-backwater is applied to the WSP model, see below.). (2) An off-shoot from the main channel with little flow and where the water surface elevation is maintained by

conditions in the main channel.

BANKFUL WIDTH: See Width, Bankful.

BETA COEFFICIENT: (1) A coefficient used to represent the change in Manning's roughness with discharge or hydraulic radius. (2) Ratio of the bed shear stress to the resisting forces of the bed-material (Shield's Parameter).

CELL: As used in PHABSIM, an increment of width of a stream channel weighted for its relative importance by a length to give an area. Defined by verticals.

CELL FACTORS: See Factors, Cell.

CHANNEL INDEX: A suitability index to the channel characteristics, usually substrate or cover.

CHANNEL ROUGHNESS: A coefficient of resistance to flow caused by particle or vegetative friction and channel features such as bends and constrictions.

CHANNEL WIDTH: See Width, Channel.

COMPOSITE SUITABILITY OF USE FACTOR: See Factors, Cell.

CONVEYANCE, FACTOR: See Factor, Conveyance.

COVER: Areas of shelter in a stream channel that provide aquatic organisms protection from predators and/or a place in which to rest and conserve energy due to a reduction in the force of the current or visual isolation, e.g., pools, undercut banks, boulders, water depth, surface turbulence, etc.

CRITICAL FLOW: See Flow, Sub-Critical and Super-Critical.

CROSS SECTION: A section across a stream channel that is perpendicular to the direction of the flow. Sometimes called a transect.

CURVES, PREFERENCE: The criteria used to weight an area as to its worth for a specific aquatic organism. The organism prefers certain conditions.

CURVES, SUITABILITY-OF-USE (SI): Same as Preference Curves except the concept of the suitability of the conditions for a specific organism is stressed.

CURVES, USABILITY: Same as Preference Curves except the concept of usability of the conditions for a specific organism is stressed.

DATUM: Any numerical or geometrical quantity or set of such quantities that may serve as a reference or base for other quantities. An agreed standard point or plane of stated elevation, noted by permanent bench marks on some solid immovable structure, from which elevations are measured, or to which they are referred.

DEPTH: The vertical distance from a point on the bed to the water surface.

DEPTH, HYDRAULIC: Equivalent to mean or average depth.

DEPTH, MEAN: The cross section area divided by the surface width.

DEPTH, THALWEG: The vertical distance of the lowest point of a channel cross section to the water surface, i.e., maximum depth of cross section.

DISCHARGE: The rate of flow, or volume of water flowing in a given stream at a given place and within a given period of time, expressed as cubic feet per second (cfs) in traditional (English) units.

FACTOR, CELL: Also referred to as Composite Suitability of Use Factor. The function of velocity (v), depth (d), and the channel index (CI) used to weight an area of stream for its value as habitat. The term is defined within the context of specific habitat models in Chapter 5.

FACTOR, CONVEYANCE: In uniform flow situations, the area available to transport water is directly proportional to Q. The Conveyance Factor (K) is the relationship between the channel and flow characteristics. The equation in traditional units is:

$$1.49 \frac{Q}{A^{2/3}} K = n$$

The discharge can then be defined in terms of K by:

$$Q = \sqrt{S} K$$

where: A = area R = hydraulic radius n = Manning's roughness Q = discharge K = conveyance Factor S = slope

FLOW: The movement of a stream of water and/or other mobile substances from place to place; discharge; total quantity carried by a stream.

FLOW, STEADY and UNSTEADY: Flow in an open channel is said to be steady if the depth of flow does not change or can be assumed constant over a specified time interval. The flow is unsteady if the depth changes with time.

FLOW, SUB-CRITICAL and SUPER-CRITICAL: In any body of moving water both inertial and gravity forces are acting on the water body. The effect of gravity on the state of flow is represented by the ratio between inertial and gravity forces, i.e., Froude Number.

If the Froude Number is less than unity, gravity forces predominate, so the flow has low velocity and is described as tranquil or streaming. If the Froude Number is greater than unity, the effects of inertia are more pronounced, so the flow has high velocity and is described as shooting, rapid, or torrential. When the Froude Number is equal to unity, flow is defined as critical.

Most instream flow studies are concerned primarily with the sub-critical state of flow, although hydraulic simulations for certain recreational activities may deal with super-critical states of flow that are difficult to model.

FLOW, UNIFORM and VARIED: Uniform flow means that the depth of flow is the same at every section of the channel. Thus, the hydraulic, energy, and bottom slopes are parallel. If the flow is varied, the depth of flow changes along the length of the channel. Varied flow is classified as either rapidly or gradually varied, depending on the distance within which the change in depth occurs. Rapidly varied flow is manifest in an abrupt change in depth, resulting in hydraulic jumps, hydraulic drops, and related phenomena. The criterion for uniform or varied flow is change in depth with respect to space.

FROUDE NUMBER: A dimensionless number used as an index to characterize the type of flow in a hydraulic structure that has the force of gravity (as the only force producing motion) in conjunction with the resisting force of inertia. As used in this document the Froude Number is:

$$VF_R = gd$$

where: F_R = Froude Number V = mean
column velocity g = acceleration
of gravity d = depth of
the water

$$\sqrt{gd}$$

GRADIENT: The rate of

change of any characteristic per unit of length. See Slope.

HEAD PIN: The terminal points in a cross section. Usually marked by something (a "pin") pounded into the ground. By convention, the first head pin is on the left-bank looking upstream.

HEIGHT OF INSTRUMENT: The elevation of the sight plane through a level. Level measurements are measured downward from this plane.

HYDRAULIC GEOMETRY: The dimensions of certain stream features with respect to both the wetted and unwetted portions of the channel.

HYDRAULIC RADIUS: Ratio of the cross-sectional area to the wetted perimeter, $R = A/P$. For relatively wide shallow channels, R approximates the hydraulic depth.

IFIM: The Instream Flow Incremental Methodology. (See Bovee, et al., 1998 and Stalnaker, et al., 1995)

LIFE STAGE: An arbitrary classification of the age of an organism into stages related to body morphology and reproductive potential, e.g., "middle age" for man and "fry" for fish.

MACROHABITAT: Habitat conditions in a reach of river controlling longitudinal distribution of aquatic organisms.

MANNING'S EQUATION: An empirical formula for the calculation of velocity in a channel. The equation in traditional units is:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

MANNING'S ROUGHNESS or MANNING's n: A factor used when computing the average velocity of flow of water in a channel that represents the effect of roughness of the confining material upon the energy losses in the flowing water. Also referred to as "n" or roughness coefficient.

MICROHABITAT: Habitat small area (cell) of a river controlling specific locations or home ranges.

MEAN DEPTH: See Depth, Mean.

PHABSIM: (pronounced P-HAB-SIM) - the Physical Habitat Simulation System. Computes a relationship between streamflow and physical habitat for various life stages of an aquatic organism or a recreational activity. PHABSIM is a component of IFIM; PHABSIM is not IFIM.

PHYSICAL HABITAT: The place where a population lives and its surroundings as defined by physical conditions, most commonly depth, velocity, and channel conditions such as substrate and cover objects.

PROFILE or PROFILE, LONGITUDINAL: (1) In open channel hydraulics, it is a plot of water surface elevation against channel distance and/or bottom elevation. (2) A line of elevations along a river usually following the thalweg. Most often includes the bed and water surface elevations.

PROFILE, TRANSVERSE: Same as a cross section.

RATING CURVE: A curve that expresses graphically the relation between mutually dependent quantities, e.g., a curve showing the relation between gage height (or stage) and discharge of a stream.

REACH: A comparatively short length of a stream, channel, or shore. The actual length is defined by the purpose of the study.

REACH LENGTH: The length of a section or piece of a river.

REYNOLDS' NUMBER - FLUID: A dimensionless number relating to the flowing force of the water to the viscous forces. It is calculated using the equation:

$$V \cdot d / \nu = ?$$

where: Re = Reynolds number ν = Kinematic viscosity of water V = mean velocity d = depth of the water

REYNOLDS' NUMBER - GRAIN (R^*): A dimensionless number used as an index to characterize the relative importance of active forces on the streambed to the viscous forces in the fluid. It is calculated using the equation:

$$\tau_* \cdot D / \nu = ?$$

where: τ_* = Shear velocity (see Velocity, Shear below) D = is a characteristic particle size ν = Kinematic viscosity of water

RIFFLE: Shallow rapids in an open stream where the water surface is broken into waves by obstructions wholly or partly submerged.

ROUGHNESS COEFFICIENT: See Manning's Roughness.

SEGMENT: Relatively homogeneous section of a stream composed of two or more reaches.

SHEAR STRESS, BED: The stress on the river bed caused by the flowing water.

SHIELD'S PARAMETER β : Ratio of the Bed Shear Stress to the resisting forces of the bed-material:

$$\beta = \frac{\tau_b}{\gamma_s (S_s - 1) D}$$

where: τ_b = bed shear stress

γ_s = unit weight of bed material (γ = unit weight of water D = bed material size S_s = specific gravity of bed material R = hydraulic radius S = slope

The terms K_s , θ^* are also used for the Shield's Parameter and D may be the mean size of the surface layer or the D_{65} of the surface area (D_{65} is where 65% of the particles are finer).

SLOPE: The inclination or gradient from the horizontal of a line or surface. The degree of inclination can be expressed as a ratio, such as 1:25, indicating one unit rise in 25 units of horizontal distance or as

0.04 length per length. Sometimes also expressed as feet per mile. **SLOPE, BOTTOM:** The change in the average elevations of the bed between two cross sections, divided by the distance between them. **SLOPE, ENERGY:** Change in total energy (potential and kinetic) available at a point. Usually approximated as the change between the cross section divided by the distance between cross sections. **SLOPE, HYDRAULIC:** The change in elevation of the water surface between two cross sections, divided by the distance between the cross sections. **SLOPE, THALWEG:** The change in the elevation of the bed, measured at the points of maximum depth, divided by the distance between cross sections. **SLOPE, WATER SURFACE:** The slope of the water surface at a point and is usually approximated as the difference in water surface elevations at two points divided by the distance along the flow path between the points. **STAGE:** The elevation, or vertical distance of the water surface above a datum (a plane of known or arbitrary elevation). **STAGE OF ZERO FLOW (SZF):** The water surface elevation at a cross section when the flow reaches zero. This is either the lowest point of the bed or the pool water surface when no flow occurs (i.e., a

downstream low bed point acts as the pool water surface control). **STEADY FLOW:** See Flow, Steady and Unsteady. **STREAMBED:** The bottom of the stream channel; may be wet or dry. **STREAM WIDTH:** See Width, Stream. **SUB-CRITICAL FLOW:** See Flow, Sub-Critical and Super-Critical. **SUBSTRATE:** The material on the bottom of the stream channel, e.g., rocks, vegetation, etc. **SUPER-CRITICAL FLOW:** See Flow, Sub-Critical and Super-Critical. **THALWEG:** The longitudinal line connecting points of minimum bed elevation along the stream course. **TOE WIDTH:** See Width, Toe **TOP WIDTH:** See Width, Top. **TRANSECT:** Same as cross section. **UNIFORM FLOW:** See Flow, Uniform and Varied.

UNSTEADY FLOW: See Flow, Steady and Unsteady. **USABLE AREA:** See Area, Usable. **VARIED FLOW:** See Flow, Uniform and Varie d. **VELOCITY:** The time rate of motion; the distance traveled divided by the time required to travel that

distance.

VELOCITY, ADJACENT: A velocity in a cell near the cell being considered.

VELOCITY, MEAN: The mean velocity may represent either a cell or a cross section. It is calculated as: V

$$Q = A$$

where: Q = the discharge in the cross section or cell A = the area of the cross section or cell.

VELOCITY, MEAN COLUMN: The velocity averaged from the top to the bottom of a stream. Usually measured at 6/10 depth or an average of values measured at 2/10 and 8/10 of the depth when the depth is greater than 2.5 ft.

$$V = \frac{1}{d} \int_0^d v \, dy$$

where: V = the mean column velocity
 v = the point velocity dy =
 small increment of depth dy
 thick d = total depth

VELOCITY, NOSE: The velocity at the point where a fish is located. This is the point velocity expressed in terms of an organism.

VELOCITY,

VELOCITY, $\mu_* = \sqrt{\frac{t_*}{\rho}} = \sqrt{\frac{t_*}{\rho/g}}$
 density of the

POINT: The velocity at a depth in the stream.

SHEAR: The square root of the bed shear stress divided by the water and has the dimension of length/time:

where: u^* = shear velocity J^* = shear stress
 on the bed (ρ = density of water)

VELOCITY ADJUSTMENT FACTOR (VAF): The ratio of the discharge for which velocities are being simulated to the sum of simulating cell velocities times cell areas:

$$Q_{\text{target}} = \sum_{i=1}^n v_i a_i$$

$$\text{ii } V = \frac{Q}{A}$$

where: Q = target discharge (Discharged to be simulated) v_i = cell velocity a_i = cell area n = number of wet cells

VELOCITY CALIBRATION ERROR (VCE): The error calculated for the relationship $v = aQ^b$ and is calculated as:

$$VCE = \frac{\sum_{i=1}^n |v_i - \hat{v}_i|}{n}$$

where: $\hat{v}$ = estimated velocity

v = measured velocity

n = number of velocity discharge pairs used to determine coefficients a and b.

VERTICAL: As used in PHABSIM, sample locations across a cross section.

WATER SURFACE ELEVATION (WSL): The elevation of the water's surface in relation to an arbitrary datum.

WATER TRANSPORT PARAMETER is $\sqrt{S}$

PARAMETER (WTP): As used in PHABSIM, the Water expressed in traditional units by the equation:

$$1.49$$

$$WTP$$

$$=$$

n where:

S = the energy slope

n = Manning's roughness **WEIGHTED USABLE AREA (WUA):** See Area, Weighted Usable. **WEIGHTED**

USABLE BED AREA (WUBA): See Area, Weighted Usable Bed. **WEIGHTED USABLE VOLUME (WUV):** The

volume of a stream weighted for its worth as habitat. **WEIGHTING FACTOR:** The value that weights a surface area or

volume area as to its worth as habitat. **WETTED PERIMETER:** The distance along the bottom and sides of a channel cross section in contact

with water. Roughly equal to the width plus two times the mean depth. **WETTED WIDTH:** See Width,

Wetted. **WIDTH:** The distance across a channel at the water surface measured normal to flow.

WIDTH, BANKFUL: The width of the stream just before the flow overtops the channel.

WIDTH, CHANNEL: An arbitrary width based on what the observer sees as a channel.

WIDTH, STREAM: Either the same as the channel width or the width of the wetted stream.

WIDTH, TOE: The width of the base of a trapezoidal channel.

WIDTH, TOP: The width of the wetted area of flow across a stream channel.

WIDTH, WETTED: The width of the stream with water in it.

Program Names

STGQ: The STGQ model uses a stage-discharge relationship (rating curve) to calculate water surface elevations at each cross section. In the stage-discharge relationship and its simulation, each cross section is independent of all others in the data set. The basic computational procedure is conducted by performing a log-log regression between observed stage and discharge pairs at each cross section. The resulting regression equation is then used to estimate water surface elevations at all flows of interest.

MANSQ: The MANSQ program utilizes Manning's equation to calculate water surface elevations on a cross section by cross section basis and therefore treats each cross section as independent. Model calibration is accomplished by a trial and error procedure to select a β coefficient that minimizes the error between observed and simulated water surface elevations at all measured discharges.

WSP: The Water Surface Profile (WSP) program uses a standard step-backwater method to determine water surface elevations on a cross section by cross section basis. The WSP program requires that all cross sections being analyzed in a given model run be related to each other in terms of survey controls and sequence upstream. That is, each cross section's hydraulic characteristics in terms of bed geometry and water surface elevations are measured from a common datum. The model is initially calibrated to a measured longitudinal profile of water surface elevations by adjusting Manning's roughness, first for the entire study site and then at each cross section. Manning's roughness is then adjusted for subsequent measured longitudinal water surface profiles at other discharges by setting the roughness modifiers used within the model. This approach requires all hydraulic controls within the modeled study site are represented by cross sections.

VELSIM: The VELSIM program is the principal tool used to simulate the velocity distributions within a cross section over the required range of discharges (i.e., the mean column velocity in each wetted cell in a study cross section at each simulation discharge). The technique relies on an empirical set of velocity observations (i.e., measured velocities) that act as a template to distribute velocities across a channel by solving for the n in Manning's equation (in this context n acts as a roughness distribution factor across the channel). The channel is divided into cells and the velocity calculated for each of these cells. The usual practice is to use one set of velocities as a template for simulating velocities for a particular range of discharges. When more than one set of empirical velocity measurements is available, a commensurate number of flow ranges can be simulated with different velocity templates. The program can be used when no velocity measurements are available. In this situation, velocity will be distributed across the cross section as a function of flow depth.

HABTAE: The primary habitat simulation program in PHABSIM. Options within **HABTAE** allow the user to select habitat calculation assuming the condition within a cell establishes the worth of the habitat in the cell. Adjacent cell conditions (for example a "feeding station") are also included in **HABTAE**. Assuming the condition in a cell simulates conditional velocity considerations plus the velocity in adjacent cells or at another location nearby establishes the worth of the habitat in the cell. The **HABTAE** program also allows habitat to be determined in terms of volume (instead of the surface area), and provides a method for determining the habitat conditions at each cross section as well as the aggregate for a study site.

HABEF: Effective habitat analysis in PHABSIM is used to determine availability of physical habitat considering two flows; in other words, the HABitat that remains EEffective when two flows are of importance. This situation often arises, for example, in the evaluation of reducing flows during the spawning period and subsequent incubation period or in hydro-peaking operations that have a daily minimum and maximum flow. In the case of spawning and incubation analyses, the spawning area at a cross section is not ‚effective’ unless the incubation period flow regime maintains the habitat in a suitable condition for the eggs to hatch.

HABTAM: The second effective habitat model is the **HABTAM** program. In **HABTAM** the species can move from cell to cell cross each transect over a range of starting and ending discharges. In this model, effective habitat is defined as the habitat that remains usable when the species is forced to move due to flow fluctuations.

AVDEPTH/AVPERM: The average parameter model, **AVDEPTH /AVPERM**, calculates a variety of hydraulic characteristics for each cross section in addition to a study site average view. These include wetted width, wetted perimeter, and wetted surface area, cross sectional area, mean channel velocity, and average depths. They can also be utilized to determine the width of a stream with water that is over some arbitrary depth(s) specified by the user. These programs provide a wealth of information at a cross section or a study site level aggregate and should be examined in most applications.

CALCF4: This utility program calculates a water transport (or conveyance) parameter (WTP) for each cross section. The program uses Manning’s equation at each cross section to calculate the WTP for each water surface elevation, develops power relationships between WTP’s, area and maximum depth, discharge and width, velocity, and average depth. The exponent (B) in the WTP regression equation between discharge and the channel conveyance factor or WTP for each cross section is an excellent initial estimate for the β coefficient for each transect in the MANSQ program.

SLOP34: A utility program that provides thalweg values, water surface elevations, and slopes in the following four tables: water surface elevation, water surface slope, energy grade line elevation and energy grade line slope.

LSTWLF: Utility program that calculates and displays the Froude number and mean channel velocities for each cross section and each flow.

Appendix 2. References

- Bain, M. B., J. T. Finn, and H. E. Booke. 1988. Streamflow regulation and fish community structure. *Ecology* 69(2):382–392.
- Bovee, K. D. 1986. Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. U.S. Fish and Wildlife Service Biological Report 86(7). 235 pp.
- Bovee, K. D. 2000. Data collection procedures for the Physical Habitat Simulation System. 114 pp. Available on the Internet at <http://www.mesc.usgs.gov>
- Bovee, K. D., B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. U.S. Geological Survey, Biological Resources Division Information and Technology Report USGS/BRD-1998-0004. viii + 131 pp.
- Bovee, K. D., T. J. Newcomb, and T. G. Coon. 1994. Relations between habitat variability and population dynamics of bass in the Huron River, Michigan. National Biological Survey Biological Report 21. 63 pp.
- Bowen, Z. H. 1996. Relations between fishes and habitat in the Tallapoosa River system, Alabama. Ph.D. dissertation, Auburn University, Alabama. 109 pp.
- Capra H., H. Breil, and Y. Souchon. 1995. A new tool to interpret magnitude and duration of fish habitat variations. *Regulated Rivers: Research and Management* 10:281–289.
- Chow, V. T. 1959. Open channel hydraulics. McGraw-Hill Publishing Co., New York.
- Collings, M. R., R. W. Smith, and G. T. Higgins. 1972. The hydrology of four streams in western Washington as related to several Pacific salmon species. U.S. Geological Survey Water Supply Paper 1968. 109 pp.
- Conover, W. J. 1980. Practical nonparametric statistics. 2nd Edition. John Wiley & Sons, New York. 493 pp.
- Doerksen, H. 1991. Two Decades of Instream Flow, A Memoir. *Rivers* 2(2):99–104.
- Felley, J. D., and L. G. Hill. 1983. Multivariate assessment of environmental preference of cyprinid fishes of the Illinois River, Oklahoma. *American Midland Naturalist* 109:209–221.
- Hawkins, P. H., and ten coauthors. 1993. A hierarchical approach to classifying stream habitat features. *Fisheries* 18:(6).
- Henderson, F. M. 1966. Open channel flow. Macmillan Publishing Co., Inc., New York. 522 pp. See List of Symbols, Chapter 1: Basic Concepts of Fluid Flow, Chapter 2: the Energy Principle in Open Channel Flow, Chapter 3: the Momentum Principle in Open Channel Flow, Chapter 4: Flow Resistance, Chapter 5: Flow Resistance – Nonuniform Flow Computations, Chapter 10: Sediment Transport.

- Johnson, D. H. 1980. The comparison of usage and availability measurements for evaluating resource preference. *Ecology* 69:125–134.
- Jowett, I. G. 1992. Models of the abundance of large brown trout in New Zealand rivers. *North American Journal of Fisheries Management* 12:417–432.
- Karr, J. R. and D. R. Dudley. 1981. Ecological perspectives on water quality goals. *Environmental Management* 5(1):55–68
- Knight, J. G., M. B. Bain, and K. J. Scheidegger. 1991. A habitat framework for assessing the effects of streamflow regulation on fish. Completion Report #14-16-0009-1550. Alabama Cooperative Fish and Wildlife Research Unit, Auburn. 161 pp.
- Manly, B. F. J., L. L. McDonald, and D. L. Thomas. 1993. Resource selection by animals: statistical design and analysis for field studies. Chapman and Hall, London, United Kingdom. 175 pp.
- Milhous, R. T., M. A. Updike, and D. M. Schneider. 1989. Physical Habitat Simulation System Reference Manual – Version II. Instream Flow Information Paper No. 26. U.S. Fish and Wildlife Service Biological Report 89(16). v.p.
- Morhardt, J. E., D. F. Hanson, and P. J. Coulston. 1983. Instream flow: Increased accuracy using habitat mapping. In *Proceedings of Water Power '83. International Conference on Hydropower* 3:1294–1304.
- Morhardt, J. E., and C. F. Mesick. 1988. Behavioral carrying capacity as a possible short-term response variable. *Hydro Review* 7(2):32–40.
- Nehring, R. B., and R. M. Anderson. 1993. Determination of population-limiting critical salmonid habitats in Colorado streams using IFIM/PHABSIM. *Rivers* 4(1):1–19.
- Railsback, S.F., R.E. Blackett, and N. D. Pottinger. 1993. Evaluation of the fisheries impact assessment and monitoring program for the Terror Lake hydroelectric project. *Rivers* 4(4):312–327.
- Rantz, S. E., and others. 1982. Measurement and computation of streamflow: Volume 1: Measurement of stage and discharge. U.S. Geological Survey Water Supply Paper 2175. 284 pp.
- Scheidegger, K. J., and M. B. Bain. 1995. Larval fish distribution and microhabitat use in free-flowing and regulated rivers. *Copeia* 1995(1):125–135.
- Stalnaker, C., B. L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow. 1995. The Instream Flow Incremental Methodology – A Primer for IFIM. Biological Report 29, March 1995, U.S. Department of the Interior, National Biological Service, Fort Collins, Colo.
- Thomas, J. A., and K. D. Bovee. 1993. Application and testing of a procedure to evaluate transferability of habitat suitability criteria. *Regulated Rivers: Research & Management* 8:285–294.
- U.S. Bureau of Reclamation. 1968. “Guide to the Application of the Water Surface Profile Computer Program”.
- Waters, B. F. 1976. A methodology for evaluating the effects of different stream flows on salmonid habitat. Pages 254–266 in J. F. Orsborn and C. H. Allman, editors. *Instream flow needs*. Special Publication of the American Fisheries Society, Bethesda, Md.

Appendix 3. ProjView

ProjView is a utility program included with the PHABSIM for Windows installation that allows the user to export the binary project files to a text format. It is intended that ProjView aid the user in recovery from software/hardware errors with the minimal amount of lost data as possible.

Output from ProjView is either a set of text files that can be viewed and edited, or a set of PHABSIM for Windows project files. Exported text files and their contents are:

Project.txt -General project information Xsec.txt -Cross section specific data Point.txt -Point specific data
Index.txt -Indexes points to cross sections Cal.txt -Calibration data Options.txt -PHABSIM option selections
Curves.txt -Suitability index curves

The exported text format files have, for the most part, a very specific format in order for the “build” options to function properly. Any editing of text files MUST follow the formats listed below.

There are two “build” options, Build and Build/Clean. The Build option builds new project files for only those checked in the selection box. The Build/Clean option performs a complete project build. As such, it requires an export of all files, with the exception of the Options file. In addition, the Build/Clean option rebuilds the Options file with default settings. This option should be used if errors to the options file would take longer to edit than it would take to reset options in PHABSIM for Windows.

Some Conventions and Comments

Lines indicated by {Note: }, {Format: }, or underlining are informational lines on format and are not part of the actual file.

Lines ending in \ are longer than the paper width and are continued on the next line. These form a single line in the text file.

Lines followed by a vertical “. . .” indicate lines missing to conserve space. Missing lines are of the same format, and the total number of lines for the section will be included in a {Note: }.

Where there are multiple data values on a single line, the positioning is important. Single data values on a line do not require specific spacing, except that when following text, there should be a space between the text and the data. Blank lines in a file should not be removed.

Where appropriate, comments are added on how errors have been repaired. Please note that, during the PHABSIM development process, it was only necessary to edit the Options file to fix corrupt datasets. Generally, it best to edit the existing file, using correct data lines as a template. When unsure about format, run ProjView on a good project and use the resulting files as templates.

Note: ProjView exports data in the order that it is stored in the project files. This is not necessarily the order in which it is displayed by PHABSIM for Windows.

Project File

The Project File contains general information about the project; name, units, discharges, etc., plus some information specific to the velocity model (N limits and beta). Discharges listed in Options File data records should match the discharges in the Project File. Likewise,

Sample File

Project: wintest Units : English N MIN: 0.000 N MAX: 0.000 BETA: 0.000 Number of calibration sets: 3 XSEC ID LIST 4

0.000 60.000 135.000 201.000 CALIBRATIONS FLOWS 3
75.200
139.000
250.000 SIMULATIONS FLOWS 4
15.000
30.100
625.000 1250.000

Point File

The Point File contains information related to each coordinate point. There is a single coordinate point per line and point IDs should match those listed in the Point Index File. Velocity values for calibration sets not used should be entered as -99.990.

Sample File

{Format: Values are ID, X, Y, Z, CI, N, units, and velocities for nine calibration sets. Note that -99.99 is used for no data.

```
123456712345678.12312345678.12312345678.12312.1231.123451231234.123\  
\1234.1231234.1231234.1231234.1231234.1231234.1231234.1231234.1231234.123\  
. 1 2.000 0.000 94.800 6.0000.00000 0 -99.990\ \ -99.990 -99.990 -99.990 -99.990 -99.990  
-99.990 -99.990 -99.990  
. 2 4.000 0.000 94.000 6.0000.00000 0 -99.990\ \ -99.990 -99.990 -99.990 -99.990 -99.990  
-99.990 -99.990 -99.990  
. 3 6.000 0.000 93.000 6.0000.00000 0 -99.990\ \ -99.990 -99.990 -99.990 -99.990 -99.990  
-99.990 -99.990 -99.990  
. 4 8.000 0.000 92.700 6.0000.00000 0 -99.990\ \ -99.990 -99.990 -99.990 -99.990 -99.990  
-99.990 -99.990 -99.990
```

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71

{Note: There is a line for each coordinate point.} .

```

154 68.000 201.000 96.000 7.0000.00000 0 -99.990\ \ -99.990 -99.990 -99.990
-99.990 -99.990 -99.990 -99.990 -99.990

```

Index File

The Index File lists which coordinate points belong to specific cross section. Coordinate Ids in the list should match coordinate Ids in the Point File.

Sample File

{Format: There are 10 indices/line at 5 spaces allocated for each point index.}

XSEC: 0.000 NUMBER OF POINTS: 44

```

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
33 34 35 36 37 38 39 40 41 42 43 44

```

. .

{Note: There is a block for each cross section. There should be a blank line between each block.} .

XSEC: 201.000 NUMBER OF POINTS: 32 123 124 125 126 127 128 129 130 131 132 133 134 135 136
137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154

Xsec File

The Xsec File contains information specific to each cross section. Cross section Ids should match those in the Project File and the number of points should match the Index File.

Sample File

{Format: Values are, in order ID, distance, upstream weight, left bank weight, right bank weight, SZF, thalweg, N, beta, slope, and number of points.

```

123456.123 123456.123 123456.123 12.123 12.123 1234.123 1234.123 / /123.123
1.123 12.12345 1234}
0.000 0.000 0.500 1.000 1.000 90.600 90.600 / / 0.000 0.000 0.00400 44
60.000 60.000 0.500 1.000 1.000 90.600 90.600 / / 0.000 0.000 0.00320 41
135.000 75.000 0.500 1.000 1.000 90.600 90.500 / / 0.000 0.000 0.00230 37
201.000 66.000 0.500 1.000 1.000 90.600 89.800 / / 0.000 0.000 0.00230 32

```

Cal File

The Cal File lists information specific to calibration data sets. There is one record for each cross section/calibration set pair. Cross section Ids should match Ids in previous files, and the number of calibration sets is given in the Project File.

Sample File

{Format: Values are Cross section, cal set ID, best estimate discharge, local discharge, left bank WSL, right bank

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

WSL, user supplied WSL.

```
12345.123 1234 12345.123 12345.123 1234.123 1234.123 1234.123}
```

Curves File

The Curve File contains the suitability index curve information. The number of curves in the file should match the number of curves listed in the Options File.

Each curve has an ID line, a species line, and a stage line. The next line is a header line followed by the number of coordinate pairs for velocity, depth, channel index, and temperature, respectively. Note that PHABSIM for Windows does not use temperature data.

Following the suitability curve point counts are the data points. Points are listed as X/Y pairs with each value using 8 spaces with 3 decimal points (8.3 format.) There are 6 X/Y pairs per line with each curve (i.e., velocity, depth, etc.) starting on a new line. Thus, a curve with 7 coordinate pairs would have 6 on the first line, 1 on the second, and the next curve would start on the third.

Sample File

Number of curves: 3 ID: 21112 Species: RAINBOW TROUT Stage: FRY

VEL DEP CI TEM

4 8 8 0

0.000 1.000 0.100 1.000 0.500 0.000 100.000 0.000

0.000 0.000 0.100 0.100 0.200 1.000 0.500 1.000 / / 1.000 0.500 1.250 0.300

3.000 0.000 100.000 0.000

0.000 0.000 1.000 1.000 2.000 1.000 4.000 1.000 / / 6.000 1.000 8.000 1.000

```

9.000 1.000 100.000 0.000 ID: 21114 Species: RAINBOW TROUT Stage: JUVENILE
VEL DEP CI TEM 5 4 8 0
0.000 1.000 1.200 1.000 1.600 0.250 2.600 0.000 / /100.000
0.000
0.000 0.000 0.400 0.000 0.700 1.000 100.000 1.000
0.000 0.000 1.000 1.000 2.000 0.500 6.000 0.500 / / 7.000 1.000 8.000 1.000
9.000 0.000 100.000 0.000 ID: 21115 Species: RAINBOW TROUT Stage: ADULT
VEL DEP CI TEM 4 4 8 0
0.000 1.000 1.500 1.000 3.000 0.000 100.000 0.000
0.000 0.000 1.000 0.200 1.600 1.000 100.000 1.000
0.000 0.000 1.000 1.000 2.000 0.700 6.000 0.700 / / 7.000 1.000 8.000 1.000
9.000 0.000 100.000 0.000

```

Options File

The Options File stores all user selections from the PHABSIM for Windows dialogs. All cross section IDs, discharges, calibration set IDs, and suitability curve IDs listed in the various sections of the Options File must match the respective value in the other files.

Example Problem Fixes

General: Often, a quick scan of the file will reveal problems. They usually appear as values of 0 or something like 128723746109238787654. Check the category and edit for the appropriate data.

Problem: The WSL method grid shows error cells (colored red) that appear whenever the project is reopened.

Solution: Check the section titled “Selected WSL Models:” and make sure every cross section/discharge combination is there and has correct method value (1 through 7 based on the dialog radio button) and a correct WSL, if needed.

Problem: Velocity calibration set assignments appear as zero when that is not the desired assignment.

Solution: Check the “VELOCITY XSEC/Q Calibration Set Assignments:” section for the appropriate cross section/discharge combinations. With the correct records, the use flag should be no less than 0 and no greater than the number of calibration sets.

Note: This problem can occur with the “WSL XSEC/Q Calibration Set Assignments” also; however, the use flag is not as straight forward. Once the correct records are in place it is best to set the use flag to 0 (all off) or 65535 (all on), and adjust the settings in PHABSIM.

Problem: Selected life stages for the habitat programs do not stay selected when reopening a saved project.

Solution: Check that the “NUMBER OF CURVES:” is correct.

Sample File

```
NUMBER OF CROSS SECTIONS: 4 NUMBER OF CALIBRATION SETS: 3 NUMBER OF DISCHARGES: 7 NUMBER OF
CURVES: 8 WSP option values:
  0 0 1 0 MANSQ option
values: 1 0 0 0 0 0 0 0
0 STGQ option values: 4 3
1 VELOCITY option values: 1
1 0 0 1 0 0 0 HABTAE
option values:
  1 0 0 0 0 0 0 0 0 1 0 0 0 0 Near Shore Distance: 0.000000 HABTAM option
values:
  0 0 0 0 0 0 0 0 0 0 0 0 0 0
AVDEPTH/AVPERM Depths: 5
  0.100 0.250 0.500 0.750 1.000 {Note: If there are no depths, the preceding line is blank.}
HABTAM Migration Flow Pairs:
  0.000 0.000
  0.0 0.000
{Note: There are 25 total lines here.} . .
.
  0.000 0.000
  0.000 0.000 HABTAM Factors for Nose Velocity Calculation Dn: 0.0000 A: 0.0000 B: 0.0000
D65: 0.0000 STGQ Cross Section Option Flags:
  xsec ID cID QT WT SZF
    0.000 1 2 4 1
    0.000 2 2 4 1
    0.000 3 2 4 1
    60.000 1 2 4 1
    60.000 2 2 4 1
    60.000 3 2 4 1
    135.000 1 2 4 1
    135.000 2 2 4 1
    135.000 3 2 4 1
    201.000 1 2 4 1
    201.000 2 2 4 1
    201.000 3 2 4 1
MANSQ Cross Section Options: xsec ID
  cID QT beta
    0.000 0 0 0.0000
    60.000 0 0 0.0000
```

135.000 0 0 0.0000

201.000 0 0 0.0000 Selected WSL Models: XSEC: 0.000 Q: 15.000 Method: 1 User WSL: 0.000 XSEC: 0.000 Q: 30.100 Method: 1 User WSL: 0.000 XSEC: 0.000 Q: 75.200 Method: 1 User WSL: 0.000 XSEC: 0.000 Q: 139.000 Method: 1 User WSL: 0.000 XSEC: 0.000 Q: 250.000 Method: 1 User WSL: 0.000 XSEC: 0.000 Q: 625.000 Method: 1 User WSL: 0.000 XSEC: 0.000 Q: 1250.000 Method: 1 User WSL: 0.000 . . {Note: One line for each cross section/discharge pair.} . XSEC: 201.000 Q: 1250.000 Method: 1 User WSL: 0.000 WSL XSEC/Q Calibration Set Assignments: XSEC: 0.000 Q: 15.000 Use: 65535 XSEC: 0.000 Q: 30.100 Use: 65535 XSEC: 0.000 Q: 75.200 Use: 65535 XSEC: 0.000 Q: 139.000 Use: 65535 XSEC: 0.000 Q: 250.000 Use: 65535 XSEC: 0.000 Q: 625.000 Use: 65535 XSEC: 0.000 Q: 1250.000 Use: 65535 . . {Note: One line for each cross section/discharge pair.} . XSEC: 201.000 Q: 1250.000 Use: 65535 VELOCITY XSEC/Q Calibration Set Assignments: XSEC: 0.000 Q: 15.000 Use: 1 XSEC: 0.000 Q: 30.100 Use: 1 XSEC: 0.000 Q: 75.200 Use: 1 XSEC: 0.000 Q: 139.000 Use: 2 XSEC: 0.000 Q: 250.000 Use: 3 XSEC: 0.000 Q: 625.000 Use: 3 XSEC: 0.000 Q: 1250.000 Use: 3 . . {Note: One line for each cross section/discharge pair.} . XSEC: 201.000 Q: 1250.000 Use: 3 VELOCITY Calculation options for Habitat Analysis

printf(line,"%8d %2d %2d %2d %2d %8.3f %8.3f %8.3f %8.3f %8.3f %8.3f %8.3f %8.3f %8.3f\n", l.ID,l.selected,l.velcalc,l.nosevel,l.velrepl,l.wmin,l.cfmin,l.Dn, l.A,l.B,l.N,l.D65,l.spg,l.CELL);

ID s v n r wmin cfmin Dn A B / / N D65 SPG CELL 12345678 12 12 12 12 1234.123 1234.123
1234.123 1234.123 1234.123/ /1234.123 1234.123 1234.123 1234.123
11300 1 0 0 0 0.000 0.000 0.000 0.000 0.000/ / 0.000 0.000 2.650 0.000
11301 1 0 0 0 0.000 0.000 0.000 0.000 0.000/ / 0.000 0.000 2.650 0.000 . . {Note: One
line for each curve ID.} .
21115 1 0 0 0 0.000 0.000 0.000 0.000 0.000/

/ 0.000 0.000 2.650 0.000 ID dist vlim vo 11300 0.000 0.000 0.000 11301 0.000 0.000 0.000
11302 0.000 0.000 0.000 11303 0.000 0.000 0.000 11304 0.000 0.000 0.000 21112 0.000 0.000
0.000 21114 0.000 0.000 0.000 21115 0.000 0.000 0.000

Maximum Migration Distances

11300 5.000
11301 5.000
11302 10.000
11303 0.000
11304 0.000
21112 0.000
21114 0.000
21115 0.000

Additional migration distance cards: 2

11301 10.000
11302 15.000

Velocity regression records: 12

0.000 1 1
0.000 2 1
0.000 3 1
60.000 1 1
60.000 2 1
60.000 3 1
135.000 1 1
135.000 2 1
135.000 3 1
201.000 1 1
201.000 2 1
201.000 3 1

Appendix 4. Integration of Channel Maintenance and Sediment Transport

One of the more important aspects of an ecologically sound flow regime is the recognition that the long-term ecological function of a stream or river corridor requires that the physical processes that form and maintain a channel must be protected. There are numerous examples where sediment transport has been either severely reduced, such as below a dam, or significantly increased, such as runoff from a watershed that has been intensively mined or burned in a forest fire. In these situations, the channel will react to the change in the sediment dynamics and either degrade or aggrade differentially along its longitudinal gradient. In some instances, a well-defined river channel will become highly braided, in other circumstances the opposite effect has been observed. This problem, of course, is not confined solely to changes in the sediment supply since alterations in the flow regime, such as seasonally maintained low flows or abstraction of the high flow component for reservoir storage, can result in changes to the dynamic equilibrium between the flow and sediment transport. This can, in turn, result in changes to channel structure and habitat composition as well as changes in the dynamics of the streamside or riparian vegetation.

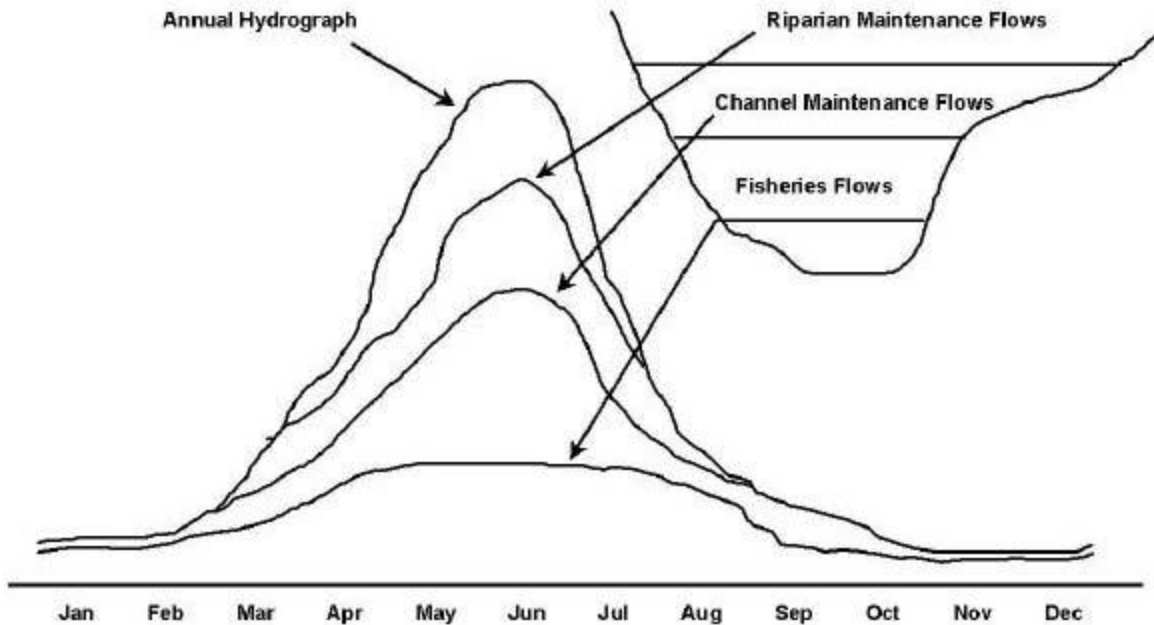
It has only been in the last decade that the importance of the physical and biological processes that maintain the interconnection between a channel and the adjacent floodplain has come into focus as a critical element of ecologically sound flows. Unfortunately, no consistent methodology has yet to be put forward dealing with what is now recognized as the three critical elements of ecologically sound flows: fishery flows, channel maintenance flows, and riparian maintenance flows. These different flow regimes are illustrated in Figure A4-1. It is important to understand that the latter two types of flow are basically related to the ability of the channel to process sediment loads and to provide adequate hydrologic connections between the stream course and the dependent riparian vegetation over some meaningful temporal domain.

We have already dealt with the use of PHABSIM as a tool to assist in the determination of the fisheries flow component of ecologically sound flows. PHABSIM analyses are well suited to examine the changes in physical habitat over flow ranges where the habitat mosaic is relatively static (i.e., after the physical and biological processes associated with channel or riparian flows have done their work within the channel). We now recognize that PHABSIM typically provides only a partial picture of the ecological flow needs and that during the higher flow periods we must turn to other methods for determination of appropriate flows during these periods (i.e., use the IFIM framework). This includes conducting analyses to determine flow regimes that maintain the channel characteristics from a physical perspective, independent of microhabitat. Identifying channel maintenance flow regimes helps to ensure that those microhabitats upon which the fish are dependent for their existence are formed or maintained during short high flow events.

In order to examine which flow patterns are needed to maintain an ecologically functioning stream system, the analyst needs to recognize that flowing water (timing, duration and magnitude) erodes, transports, and deposits sediment as well as controls the types and growth patterns of vegetation species in generally predictable ways. The temporal distribution of the magnitude and duration of flows interacts with the resident geology, topography, and vegetation to ultimately determine the form and condition of the mesoscale and microhabitat distribution of habitat upon which fish and other aquatic organisms are dependent for their living space. Alteration of the flood flow regime in a river can ultimately result in loss of side channel habitats, changes in riparian species and distribution, and alteration of the ratio of pools to riffles. Therefore, these factors need to be carefully considered in any analysis of altered flow regimes and are not restricted to the high flow component. Seasonal reductions in flow at artificially low sustained levels can also result in the accumulation of fine sediments that are deleterious to successful spawning and egg incubation of many species.

Figure A4-1. Elements of the hydrograph to consider when describing an ecologically sound flow regime.

In order to examine which flow patterns are needed to maintain an ecologically functioning stream system, the



analyst needs to recognize that flowing water (timing, duration and magnitude) erodes, transports, and deposits sediment as well as controls the types and growth patterns of vegetation species in generally predictable ways. The temporal distribution of the magnitude and duration of flows interacts with the resident geology, topography, and vegetation to ultimately determine the form and condition of the mesoscale and microhabitat distribution of habitat upon which fish and other aquatic organisms are dependent for their living space. Alteration of the flood flow regime in a river can ultimately result in loss of side channel habitats, changes in riparian species and distribution, and alteration of the ratio of pools to riffles. Therefore, these factors need to be carefully considered in any analysis of altered flow regimes and are not restricted to the high flow component. Seasonal reductions in flow at artificially low sustained levels can also result in the accumulation of fine sediments that are deleterious to successful spawning and egg incubation of many species.

Maintenance of stream and river ecosystems hinges on the determination of flow regimes that protect the physical processes, which in turn influence the biological processes within the stream or river. This results in the concept of multiple flow regimes that target specific elements of the flow such as fisheries, channel maintenance, and riparian maintenance flows.

Channel Maintenance Flows

Channel maintenance (or fish habitat maintenance) flows represent that portion of the hydrograph that is high enough to prevent vegetation growth within the active channel and remove sediment. The active channel can be characterized as that elevation within the channel associated with bank-full flows and is typically indicated by flat areas of alluvial deposits and the line of perennial vegetation that makes a well-defined margin along a stream or river corridor.

Although a fairly wide range of flows are associated with bank-full discharges across different river systems, flows associated with a return period of approximately

1.5 years have been identified as an average value for these types of flows. Some investigators have also determined that the bulk of sediment transport on an annual budget occurs at intermediate flow ranges and that the most effective discharge in terms of long-term sediment budgets is nearly equivalent to the discharge at bank-full. These studies indicate bank-full flows are an important hydrological benchmark that is related to the flows, which are critical to maintaining the shape of alluvial channels and therefore, the mesohabitats upon which they are dependent.

Site-specific studies that measure the bank full discharge directly or are modeled from observations of the elevations of riparian and sediment deposition areas can be undertaken as an integral part of an IFIM application. Once the magnitude of the bank full flow has been determined, it can be used in conjunction with other information to determine this part of an ecologically acceptable flow regime. Other considerations of these higher flows relate to how the timing of the reduction of the high flows may be impacted by a project. For example, a rapid reduction in high flows has been observed to result in an increased sediment flow to rivers from bank failure due to rapid loss of hydrostatic pressure in the banks.

In some instream flow studies, the anthropogenic reduction in the high flows have been constrained to no more than a 10% reduction from the previous peak daily flow in order to minimize these types of secondary effects. Although not developed from a rigorous analytical procedure, these flow reduction criteria were derived from an examination of the long-term historical daily hydrographs for a number of similar river types and selecting a flow reduction range at the upper limit of observed natural processes. Most natural high flows do not decrease this rapidly and a more stringent requirement may be warranted. Reducing the duration of the peak flows may in fact impair some channel forming processes as well as impacting riparian species seeding and growth dynamics that are tied to these characteristic patterns in flow reductions. It should also be apparent that a careful examination of the flow reduction pattern should be considered in light of not only the riparian vegetation needs but also to minimize potential impacts associated with fish stranding if appropriate. Utilization of the PHABSIM cross section geometries in association with water surface elevation modeling can provide some insights to appropriate flow reductions over specific flow magnitude ranges.

Riparian Maintenance Flows

As with most conceptual tenants of instream flows, to date no universally accepted or recognized methods have been developed for the determination of flow quantity or duration needed to maintain riparian habitats and associated flood plains. In this context we take riparian flows as those not only necessary for the riparian vegetation immediately adjacent to the active channel but also side channels, oxbow lakes, wetlands, swamps, and ponds. Often these types of habitats are only seasonally connected to the main river channel but in turn may represent critical breeding or rearing areas for many fish species and in fact are necessary for successful completion of their life cycles. In addition, the overall importance of these types of habitats in terms of the general ecological diversity and function of a river corridor cannot be overstated.

Existing methods concentrate on modeling flows at which the water surface elevations inundate the flood plain where these riparian features are present within the affected study reaches. As with the channel maintenance flows, these site-specific issues and features can be identified during the scoping, fieldwork, and analysis phases of an IFIM application by making the appropriate cross section geometry measurements and extending them as necessary to pick up critical elevation features. The investigator is still left with determining the seasonal and duration aspects of these flows and inclusion of a riparian and terrestrial wildlife biologist when planning the analysis is strongly recommended for studies in which these types of issues are deemed important.

Including Sediment Analysis for Medium to Low Flow Issues

As a final note, we strongly encourage investigators to consider sediment transport as part of the overall instream flow assessment. Characterization of the various sediment size distributions within the study stream can permit simple calculations of the flow at which various size fractions can be moved. This would permit the investigator to determine, for example, in a stream where a significant proportion of the sediment load during medium to low flows is sand or silt, whether or not a proposed flow reduction would be expected to result in conditions in which these size fractions would no longer be transported. This would imply that deposition of these materials in slower water areas of the reach would occur and allow the investigator to evaluate the potential impacts on egg incubation and potential changes in invertebrate community structure associated with the changes in channel substrate characteristics.

Laboratory 1. Using the PHABSIM for Windows Interface

Introduction

The PHABSIM Windows interface considers all hydraulic and habitat simulation work planned for a study site to be one "project". All data entry, selection of simulation options, output option selection, and viewing of results takes place within the project. The purpose of Laboratory 1 is to familiarize the user with use of the interface to build a PHABSIM project data set.

Using the Menu System

The general steps to use the interface consist of creating a new project or opening an existing project; importing, entering, or changing data; entering or changing run options; running programs; viewing intermediate and final results; saving the project files; and capturing results in a format for creating reports. In the laboratory exercises, each of those steps is presented in the following format:

\Main Menu\Next Menu\Next Menu or Tab: followed by instructions.

For example, to enter cross section coordinate data for the second cross section, the user clicks on Edit, followed by clicking Cross Sections, followed by selecting the second cross section, followed by clicking the Coordinate Data tab, and then entering data in the spreadsheet-like interface. That sequence of operations is noted in the documentation as:

\Edit\Cross Sections \Number\Coordinate Data: Enter x, z, channel index, n (if known), VelSet1, VelSet2, ...

The actions are:

Move mouse to **Edit** item in the main menu, click. Move mouse to **Cross Sections** tab, click. Move mouse to the gray **box showing number 2** in the left column, click. Move mouse to **Coordinate Data** tab, click. Enter data in the spreadsheet-like interface as described below.

Abbreviated notation, for example **..\Coordinate Data**, is used in some places to abbreviate **\Edit\Cross Sections \Number\Coordinate Data** when moving within the same set of tabs or menus.

This notation convention is used through out the Laboratory exercises. If you find the notation is too terse or confusing, click on the first item that comes to mind and see what happens. Until the data entries or option selections are changed, you are merely viewing different portions of the interface so you can click on each successive item in this notation and follow where it leads.

To gain familiarity with the interface, we will begin by loading an existing project and navigating through the interface to get a feel of the process. First open the project:

Step 1. Open a Project

\File\Open Project: Navigate the Windows File Menu to \If310\Newlabs\Lab01 and double click on the file Lab1.phb

Step 2. Enter and Edit Cross Section Data

Data can be entered and viewed in the Edit area. Look at the cross section data in the Sampl1 project by:

\Edit\Cross Sections \Cross Section Data

Note that the data set contains four cross sections. For each cross section, the following information has been entered.

ID – The cross section identifier. *In PHABSIM for Windows we always use the distance from the downstream cross section as the identifier. This allows a cumulative upstream distance to be calculated and displayed as the Y ordinate in the coordinate data tab.*

Length – the cross section length or the distance from the downstream cross section. Length is used to calculate the y (cumulative distance) value. Cross sections are sorted by the cross section ID in ascending order.

Upstream WF – the weight assigned to this cross section. That is, the fraction of distance upstream it represents. **L**

Bank WF – the left bank weight for a bend. **R Bank WF** – the right bank weight for a bend. If these are equal, there is no bend. **SZF** – stage of zero flow.

N – Manning's n value for the cross section. **Beta/D50** – beta exponent for use in the MANSQ program, if applicable, or median substrate particle size in mm.

Slope – energy slope at the cross section. Typically estimated as the water surface slope. To edit or view individual cross sections use:

\Edit\Cross Sections\Coordinate Data

Under this tab, the cross section currently highlighted under **Edit\Cross Sections \Cross Section Data** will be displayed. Cross section ID is shown above the table and the number of points on the cross section is also displayed. To view the cross section profile, click the **Graph** button. You may drag the graph and Cross Section Data windows by their top bars so both can be viewed simultaneously. To view a different cross section, return to the **Cross Section Data** tab and click on a different cross section. The highlighted region will change. Return to the **Coordinate Data** tab and the graph will update.

The **\Edit\Cross Sections\Calibration Data** tab allows entry of data for left and right bank water surface elevations, the user-determined (or “given”) water surface elevation, the “best estimate” discharge for the site, and the discharge measured at that cross section. As with the coordinate data, cross sections are selected in the **Cross Section Data** tab prior to viewing the **Calibration Data** tab for that cross section.

Entering and Editing Suitability Curves

Now that you have seen how to navigate around the cross section editing menu, take a look at the **\Edit\Suitability Curves** menu. You will find a similar set of menus and tabs there. Look at the data entry and display area for habitat suitability curves using:

\Edit\Suitability Curves

The **\Edit\Suitability Curves\File** menu item allows you to create a new curve, import an existing curve file from another project, copy curve files, and save curve files. The **\Edit\Suitability Curves\Curve** menu item allows you to choose which curve in a suitability curve set is displayed in the data entry box. For example: by selecting **..Curve>Select by ID** you can view a list of all HSC curve sets currently entered into this project and select a particular curve for viewing. Individual curves for depth, velocity, channel index, or temperature are selected using the **Curve Type** buttons to the right. **\Edit\Suitability Curves\Graph** allows you to display a graph of the selected curve values displayed in the SI curve-editing box. These graphs can be scaled for a better view. See Chapter 1 for use of the mouse button graphing features in PHABSIM for Windows.

The **\Edit\Suitability Curves\Curve\Display All Curves** menu item displays the four HSC curves in one window.

Entering and Editing Simulation Discharges

This simple dialog allows you to start with a small number of simulated discharges to be used in calibrating the hydraulic models, then add additional discharges for final simulation runs. For calibration when comparing observed with simulated conditions, the calibration discharges have been entered as simulation discharges by default. They cannot be removed and will appear in all simulations you run. The calibration discharges are shown in gray and any other discharges you enter will be shown with a white background.

To add discharges to this list, either place the cursor on the next highest discharge and press the Insert key on the keyboard or, to add a discharge higher than the highest shown, place the cursor on the last discharge and press the down arrow. Either of these actions will provide a new row with a discharge of 0. You simply type the desired discharge value in the highlighted cell.

Step 3. Running the Models

The **\Models** menu is where you set-up and run the various models. Here hydraulic simulation is divided into water surface and velocity simulation and habitat simulation includes the Habtae, Habtam, and Habef models. Also included here is a combined Avdepth\Avperm model. Each model contains a **Run** button that is clicked after all of the model input parameters are selected.

Further instructions in running the models are contained in the remainder of the laboratory exercises.

Step 4. Close and Save the Project

To prepare for the next laboratory exercises, please close this project using:

\File\Close Project

If you had made any changes to your project, they would be saved now. The system will prompt you to save your project if changes have been made. In general it is a good idea to frequently use:

\File\Save Project

You may wish to save the project periodically to ensure you can recover from a mistake or a computer glitch.

Step 5. Manipulating PHABSIM for Windows Graphics

PHABSIM for Windows uses a third-party graphics package that allows the graphs displayed by clicking the various graphics buttons described in the labs and manual to be scaled, translated, zoomed and, in some cases, rotated. The following examples illustrate each of those functions.

Scaling (Figures L1-1 and L1-2):

- Press Ctrl and hold down both mouse buttons
- Move mouse down to increase the chart's size
- Move mouse up to decrease the chart's size

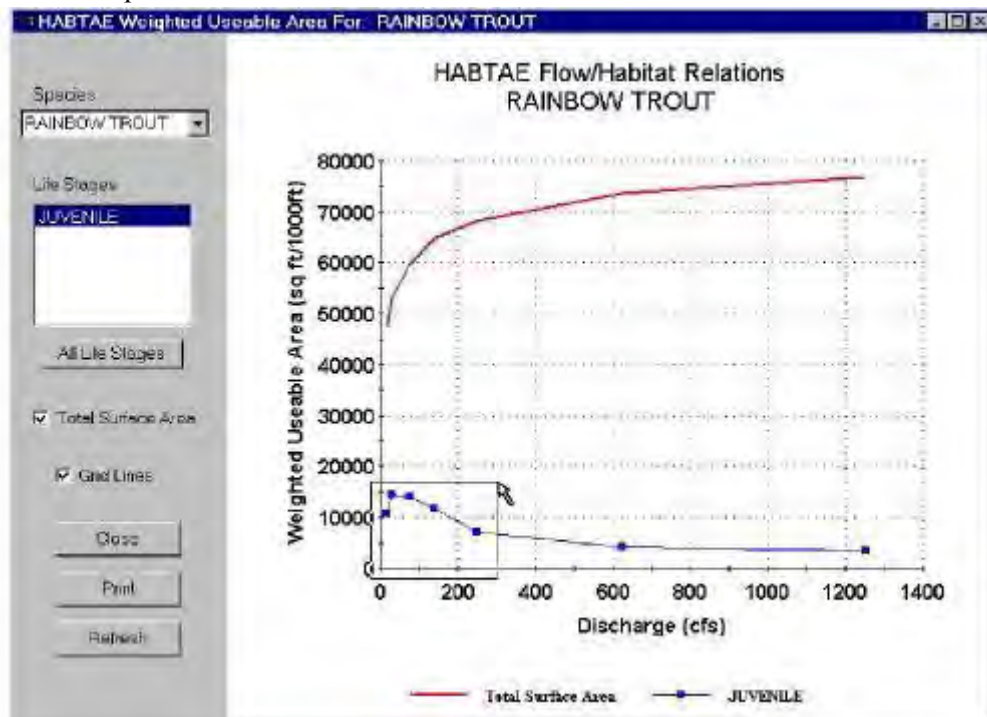
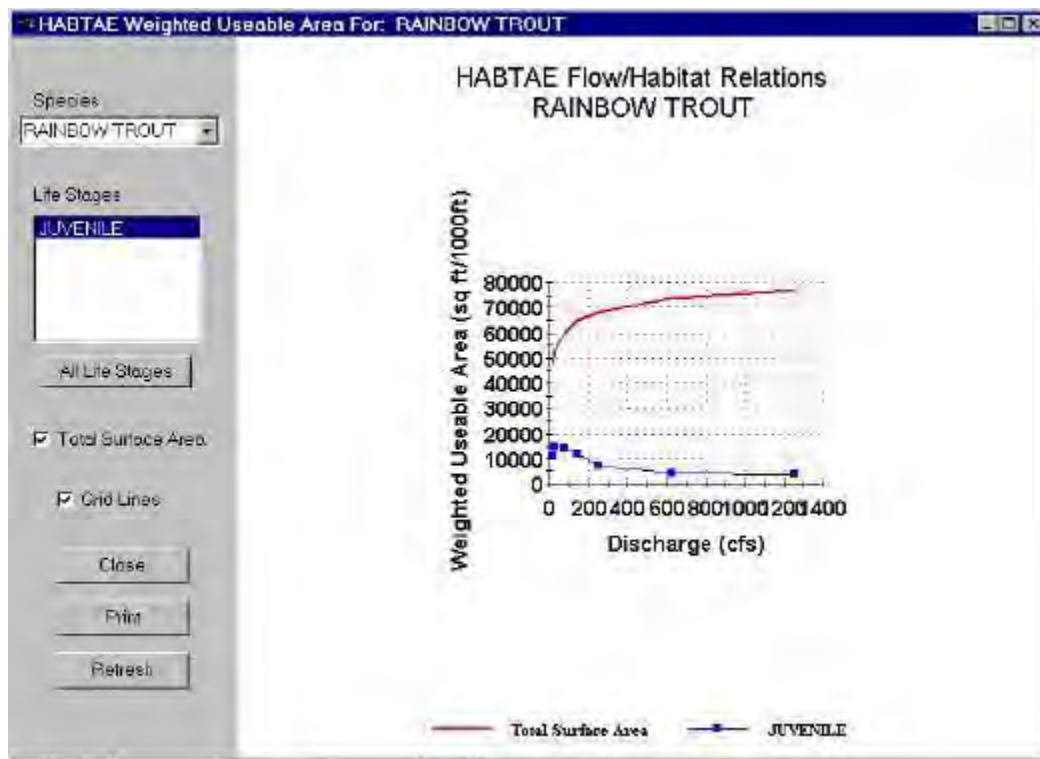


Figure L1-1. Original image. Figure L1-2. Scaled view.



Translation (Figure L1-3)

- Press Shift and hold down both mouse buttons
- Move mouse to shift the chart

Zooming

Axis Zoom

- Press Shift and hold down the left mouse button
- ☐ Move mouse to select the area to Zoom into (a box will be drawn around the area) then release the button
- Axis zoom is illustrated in Figures L1-4 and L1-5. Graphics Zoom does not retain axes, otherwise, same as Axis Zoom
- Press Ctrl and hold down the left mouse button
- Move mouse to select the area to Zoom into and release button

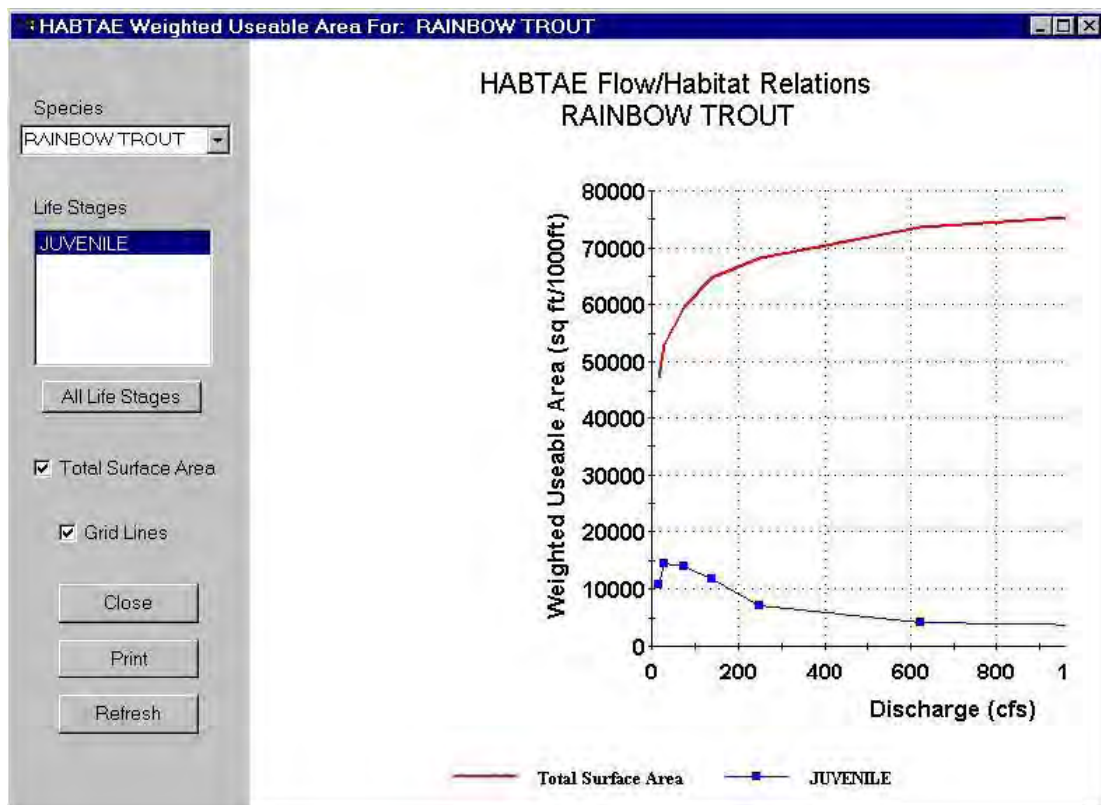


Figure L1-3. Translated image.

Rotation (3-D charts only, Figures L-6 and L-7)

- Hold down both mouse buttons
- Move mouse left and right to change the rotation angle
- Move mouse up and down to change the inclination angle

Return to Default Position (Fig. L1-8)

- Press "r"
- All interactive scaling, translation, and zooming is removed

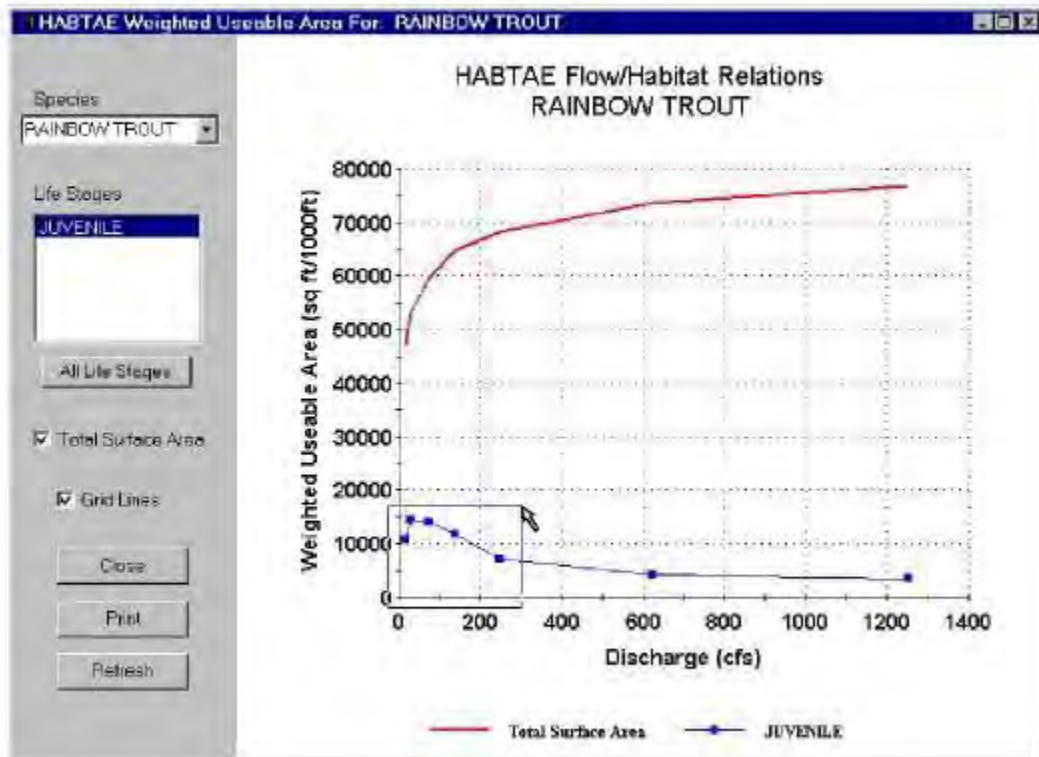
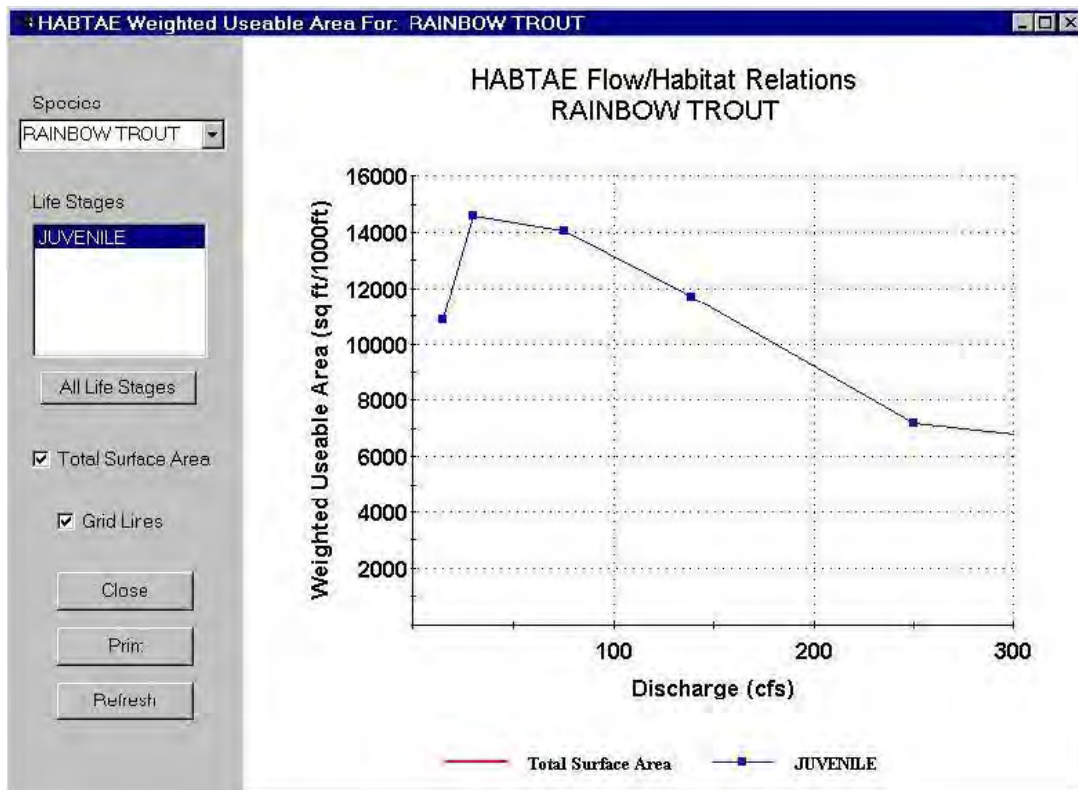
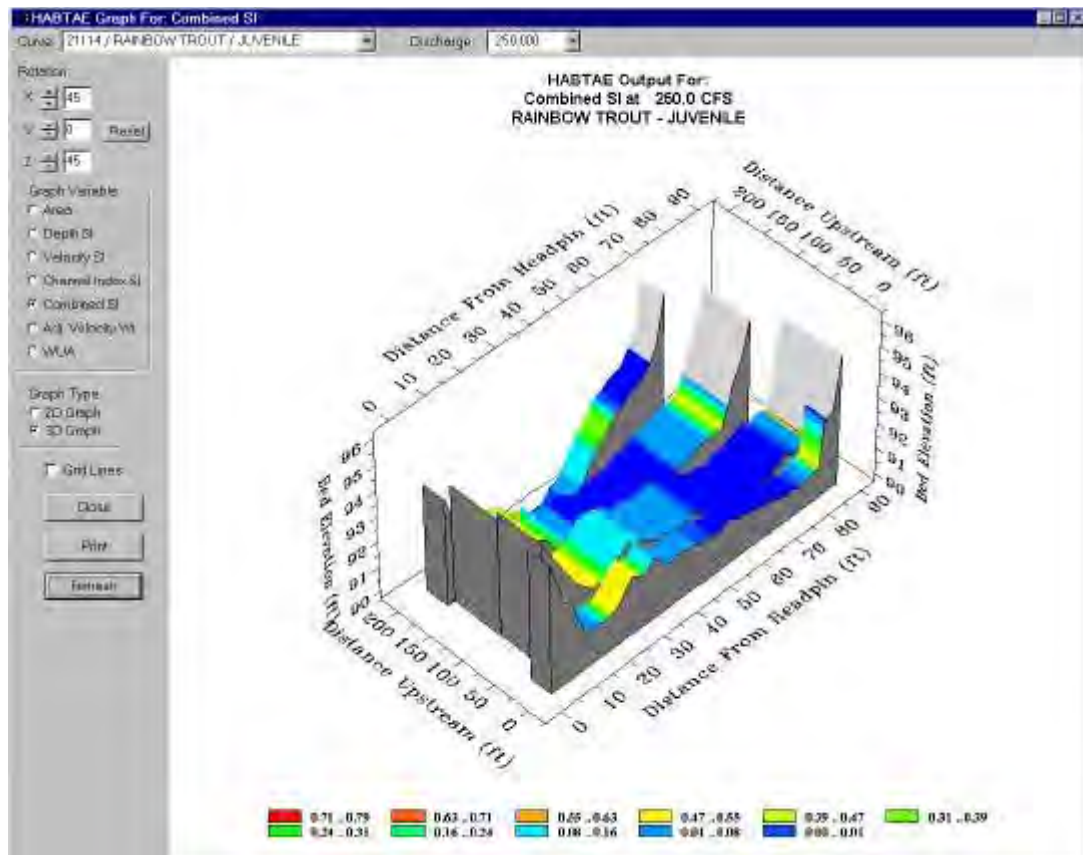
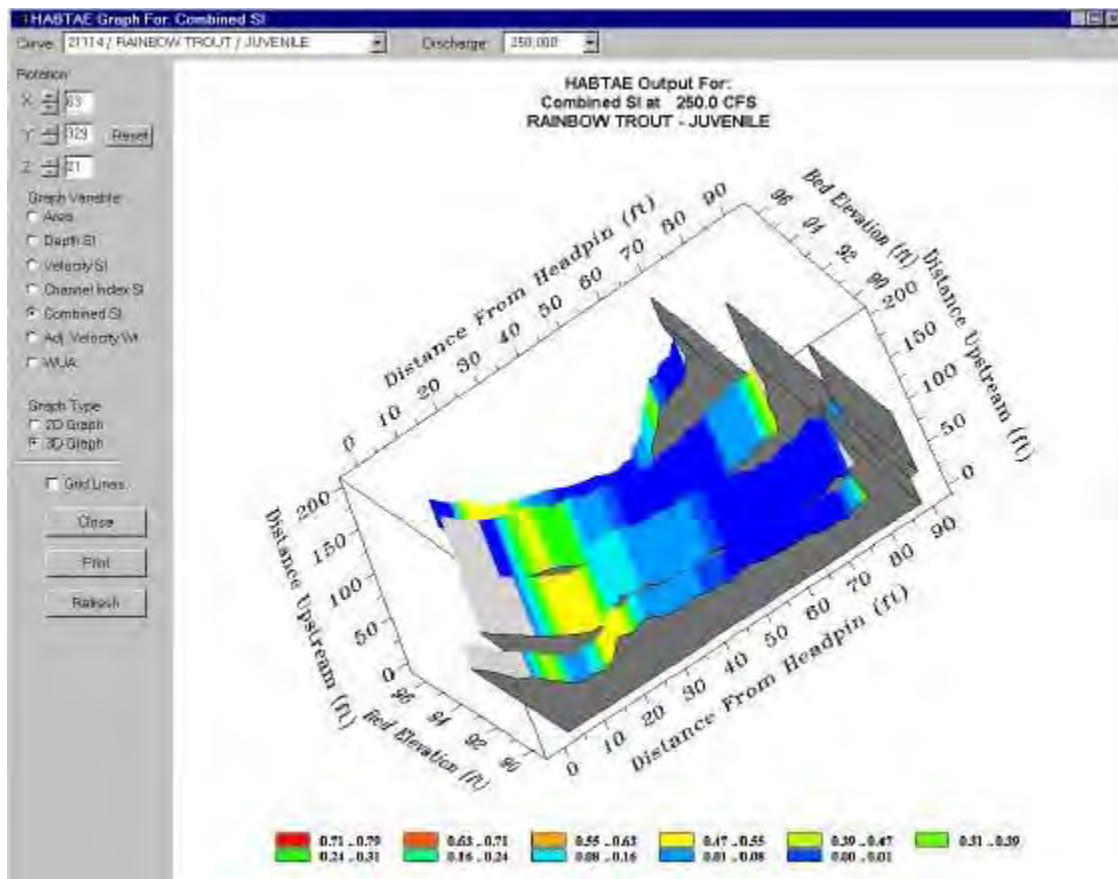
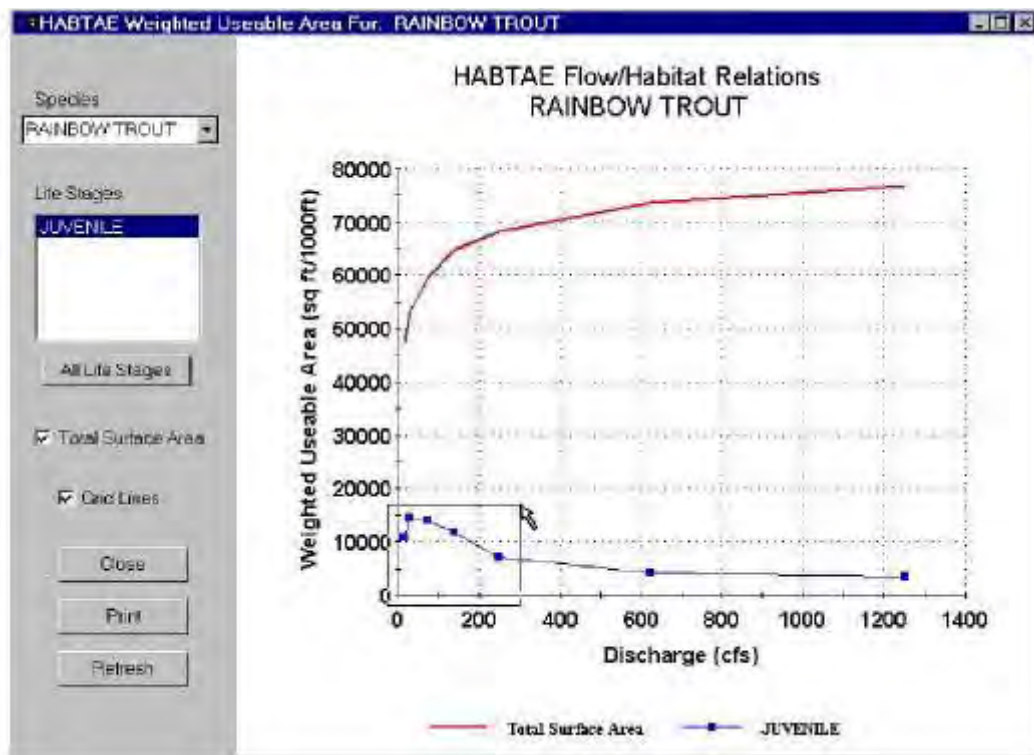


Figure L1-4. Selecting a region to enlarge. Hold Shift and Left Mouse button, drag box to desired area. **Figure L1-5.** Zoomed view appears when mouse button is released. **Figure L1-6.** Default position of 3-D chart. **Figure L1-7.** Rotated 3-D chart. **Figure L1-8.** Press “r” o keyboard to return to original view.









A Strategy for Using PHABSIM for Windows

PHABSIM for Windows was designed to be used in combination with other Windows features to allow a large degree of flexibility in the PHABSIM analysis. The following suggestions constitute a strategy for using Windows to the maximum advantage while doing a PHABSIM analysis.

Monitor Adjustments

We have found it is most convenient to adjust your monitor to display the maximum number of pixels that can comfortably viewed. Current generation 17-inch monitors can reliably display 1024 x 768 pixels with font sizes in the range of normal printed text. If you can comfortably use 1280 x 1024 pixels you will find additional utility in being able to position various windows on the desktop for convenient use. The minimum resolution monitor that can be used with PHABSIM for Windows is 800 x 600 pixels. You may find that a 19-inch monitor operating at 1280 by 1024 pixels facilitates the analysis by allowing multiple windows to be open simultaneously.

Location of the Working Directory

PHABSIM for Windows places the sample files in C:\My Documents\Phabsim\Sample1 and ..\Sample2. This location was chosen solely because most computers using Microsoft Windows will have

a My Documents directory on the C: drive. You may place your working directory for any project in the desired location at project creation. This may be accomplished by creating the directory using the **Browse** feature in the **\File\Open Project** dialog or by creating the directory prior to running PHABSIM for Windows using Windows Explorer. Place the working directory in a location that is relevant to your project and easy to remember.

The PHABSIM Window

The main program window need not be maintained at its full size. The primary purpose of the main window is to provide the top-level menu items in the menu bar. Thus, after a project is opened, the main PHABSIM window may be sized so only the menu bar or the text in the project description is displayed. This opens up space on the desktop without losing any of the main menu functionality. Drag the lower right corner of the window to resize it.

Displaying Graphs

Many of the plots of input data or model results display values that are either entered or displayed using various interactive tables in the PHABSIM for Windows interface. It is often convenient to drag the graph window to the lower right of the screen and drag the data entry or program option window to the upper right so at least portions of the data table may be viewed at the same time as the graph. Graph windows may be resized by dragging their corners.

The Desktop

We have found that it is very convenient to place icons on the desktop for PHABSIM, Projview (a PHABSIM file translation utility), Notepad, and Wordpad (also called Write). It is also convenient to have an icon for your spreadsheet program to provide ease of starting the spreadsheet by simply double clicking the icon.

A convenient way to capture PHABSIM for Windows graphics (other than printing them) for use in other documents is to use the Print Screen feature of Windows and paste the graphic into Microsoft Paint. Thus, placing an icon for Paint on the desktop may also be convenient.

PHABSIM for Windows produces numerous files that can provide ancillary information during the course of the analysis. It is convenient to have Windows Explorer running while using PHABSIM so those files may be accessed by simple drag and drop actions from Windows Explorer to the other programs noted here that are placed on the desktop.

Auxiliary Programs

Spreadsheet Program

Though PHABSIM for Windows contains numerous automatically generated plots that can be used to display both input data and the results produced by the various models within the program, the plotting package can only display results from the current analysis. Thus, when the user wishes to compare results of different analyses, it is necessary to export those results to a different medium using cut and paste operations. We have found it very convenient to create spreadsheets for this purpose. Later lab exercises use spreadsheets to calculate differences between model results based on different model options and to display those different results graphically. When spreadsheets are used in conjunction with PHABSIM for Windows, the spreadsheet files should be saved with the PHABSIM files and should become part of the analysis record.

Notepad

While applying PHABSIM to a study site, numerous decisions are made regarding program options, data issues, and alternative approaches to describing habitat for the site. It is very difficult to recall each decision after the study is done. Thus, we suggest that the user create a Notepad file with a name like "Projectlog.txt" and keep a diary of the progress of the analysis including any problems encountered, the program options selected, and especially why they were selected, and any other pertinent information that will allow later defense of the study. For example, such a log file would be a good place to keep track of calibration error statistics and notes as to why a particular calibration was deemed satisfactory.

Windows Explorer and Wordpad

In addition to the results tables provided in the PHABSIM for Windows interface, the program produces numbered *projectname.ZOUTxx* files that contain computational details and other numerical results from running the models. Viewing these files facilitates some portions of the analysis. It is convenient to be able to "drag and drop" the numbered ZOUTxx files from Windows Explorer to Notepad for viewing. Some of the files will be too large for Notepad, but Wordpad will be able to display them. Further, Wordpad provides more formatting control, when portions of the ZOUT files are to be inserted in reports, than Notepad.

Use Strategy

When doing a PHABSIM analysis, the strategy we have found most convenient is to open and minimize the following programs and files:

- Notepad, open the log file
- Spreadsheet, open data comparison or error tracking file(s)
- Windows Explorer, move to the working directory so you can drag and drop conveniently

The minimized programs will show as buttons on the task bar at the bottom of the screen. Click on the appropriate button to access them. Remember to save your log, PHABSIM and spreadsheet files often during the course of the analysis. Such a strategy will prevent data loss due to the occasional inevitable mistake.

Laboratory 2. Building a PHABSIM Project

Objective

The objective of this laboratory is to cover the use of PHABSIM for Windows to create a PHABSIM project file. PHABSIM for Windows will be used to create an example project file and the project will be reviewed for errors.

Data Files Used: Data.xls

Introduction

In typical PHABSIM applications, the user will likely have a number of cross sections where the hydraulic characteristics of the river channel have been measured at one or more discharges. In this laboratory, we have provided data collected at four cross sections from the Fryingpan River, where water surface elevations and velocities have been measured at three calibration discharges. All the hydraulic data necessary to create a complete PHABSIM project file have been summarized in tabular form by cross section and provided in Tables L1-1 to L14 at the end of this lab. Information about reach lengths, Stage of Zero Flow (SZF), upstream weighting factors, reach length, slope, best estimate of the discharge, and measured discharge at each calibration flow is located at the top of each tabular summary. The remaining data in the table lists the x-distance, bed elevation, channel index, and observed velocities at each of the calibration flows.

The laboratory illustrates use of **\Edit\Cross sections** to enter the data for the four cross sections. Two complete PHABSIM project data files containing these calibration data have already been created (SAMPLE1.PRJ and SAMPLE2.PRJ) as example data files. SAMPLE1.PRJ contains data entry only, while SAMPLE2.PRJ has been run through the habitat simulation stage. Both projects are included on the PHABSIM distribution disks. Proceed through the steps in order. If you run out of time to enter all the data described below, you can use SAMPLE1 to navigate the various menus and view diagnostic plots. A separate set of worked laboratory exercise project files is provided for each lab. The location of those files will vary depending on the computer system used for class instruction.

Step 1. Create a New Data Set

Now that you understand the basic PHABSIM for Windows navigation process from Lab 01, you are ready to open a new project and enter data.

For ease of reference these instructions will use the Project name MYLAB02.

\File\Open Project: Enter a project name in the **Project folder name** box. Then type a description of the project in the **Project Description** box. (The description is limited to 256 characters.) Next use the **Browse** button to navigate the Windows file tree to where you want the new folder to be stored. PHABSIM for Windows will create a directory and a set of files with the project name. For this lab, enter the new project name (i.e., MYLAB02) in the file name box, enter an appropriate description in the project description box, then click **Browse** and navigate to \F310\Laboratories, and click **OK**. (See Figures L2-1, L2-1, and L2-3.)

Figure L2-1.
Opening a new
project.

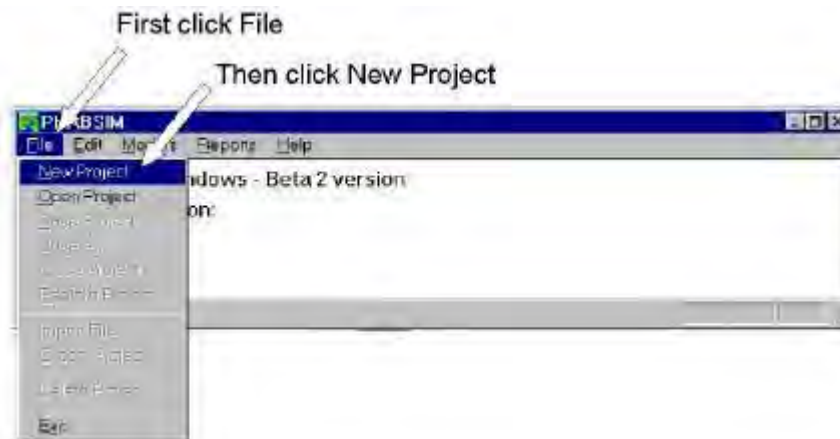
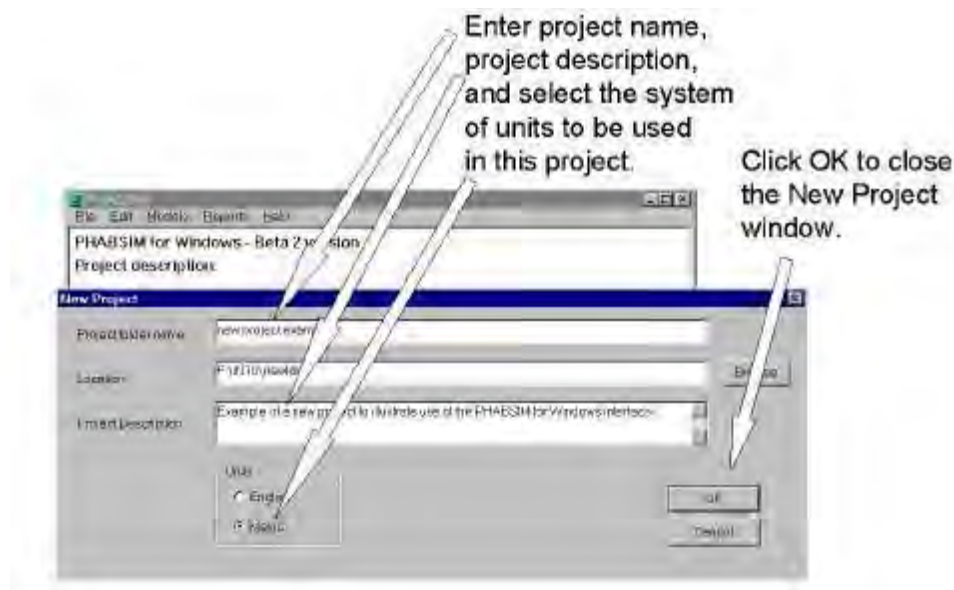


Figure L2-2.
Assigning a
folder location.

Figure L2-3.
Entering project
name and
description.





An example of a project description might be:

“Fryingpan River 3 miles downstream from Reudi Reservoir. High flow data collected May 10, 1999, mid flow data collected July 10, 1999, and low flow data collected Aug. 23, 1999. By name, name, and name.”

You can revise the project description from the Edit menu using **Edit\Project Data**. This allows adding short notes on the status of the analysis as the process progresses.

Step 2. Enter Project Hydraulic Data for Lab02

To build a project’s data set, click the **Edit** menu item. You are presented with choices of **Cross Sections**, **Suitability Curves**, and **Discharges**. You can enter and change data for each of these categories by selecting the corresponding menu item. However, you must begin with **Edit\Cross Sections\Cross Section Data** and enter the cross section data for at least one transect (cross section) prior to entering calibration data or coordinate data as shown in Figure L2-4. The Edit\Cross Sections dialog contains three tabs for **Cross Section Data**, **Calibration Data**, and **Coordinate Data**. The **Cross Section Data** tab is displayed by default.

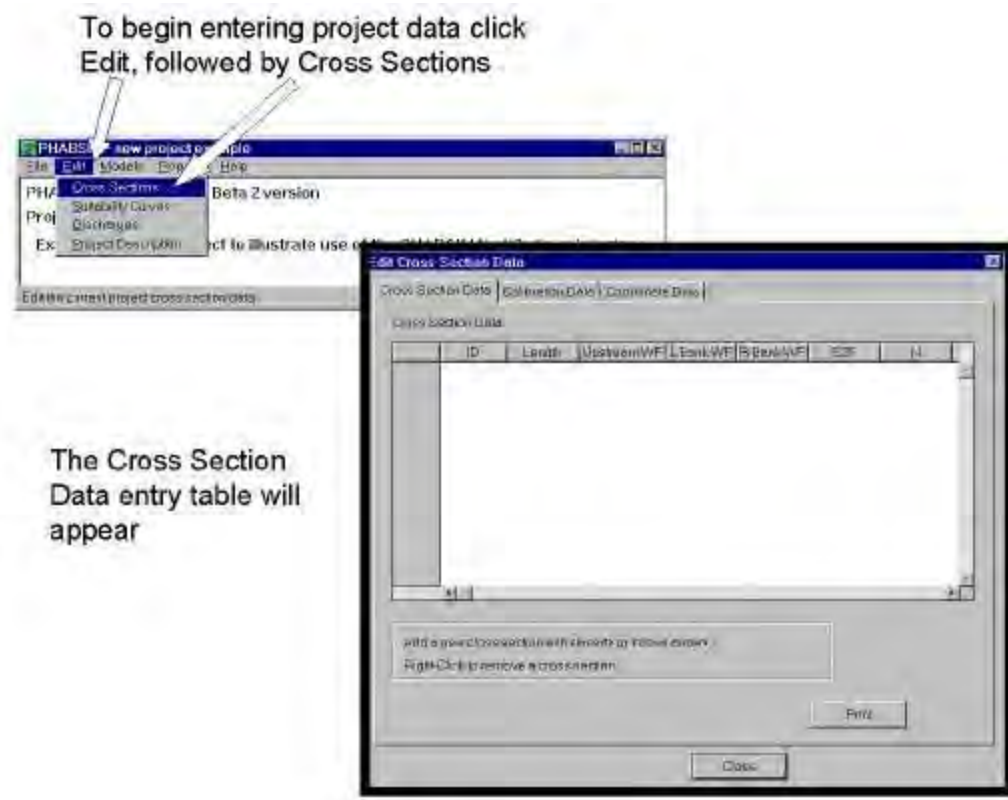


Figure L2-4. Preparing to enter cross section data.

To create a new cross section, in the **Cross Section Data** tab, use the down arrow. A row of cells appears with a cross section ID number of “-1.00”. For each cross section, enter the id for the cross section by typing the cross section ID from Table L2-1 over the -1.00 entry. Move the highlight cursor to the right with the right arrow and enter the reach length. Continue moving to the right and enter the upstream weighting factor, the bend weights for the Left Bank and Right Bank, the stage of zero flow (SZF), Manning’s n value (if known), Beta coefficient for MANSQ (if known), and the energy slope. Values for Manning’s n and beta can be left unchanged for now. You would enter those values when using the WSP or MANSQ models later in the analysis. Your data for the first transect should now contain the

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

PREFACE

A Brief History of PHABSIM

following values.

Complete the cross section data table as shown in Figure L2-5. Scroll right to include beta and slope values. **Figure L2-5.** Entering cross section data.

Press the down arrow on the keyboard to begin data entry. A new line of cross section data will appear as shown



Then enter (overtyp) cross section ID, length, weighting factors, stage of zero flow, Manning's n, MANSQ Beta coefficient, and energy slope for the cross section. Use the scroll bar (right) to view Beta and slope.

	ID	Length	Upstream WF	L Bank WF	R Bank WF	SZF	n
1	0.000	0.000	0.500	1.000	1.000	0.000	0.033
2	50.000	50.000	0.500	1.000	1.000	50.000	0.040
3	75.000	75.000	0.500	1.000	1.000	75.000	0.030
4	100.000	100.000	0.500	1.000	1.000	100.000	0.045

An example with data for four cross sections is shown at left.

Next, click on the cross section ID 0.00 line and proceed to the **Calibration Data** tab (Fig. L2-6). Enter data for either left and right bank water surface elevations, or a single “user” selected water surface elevation, the user-determined or “given” discharge for the study site, and the measured discharge for the current transect. Enter these items for each calibration discharge (matching each VEL set) for this study. Return to **..Cross Section** tab to change to the next cross section ID.

Note that the best estimate discharge must be a unique value (duplicates are not allowed). After you enter calibration data and exit the calibration data tab, the table sorts in ascending order on the **Best Estimate Q** values.

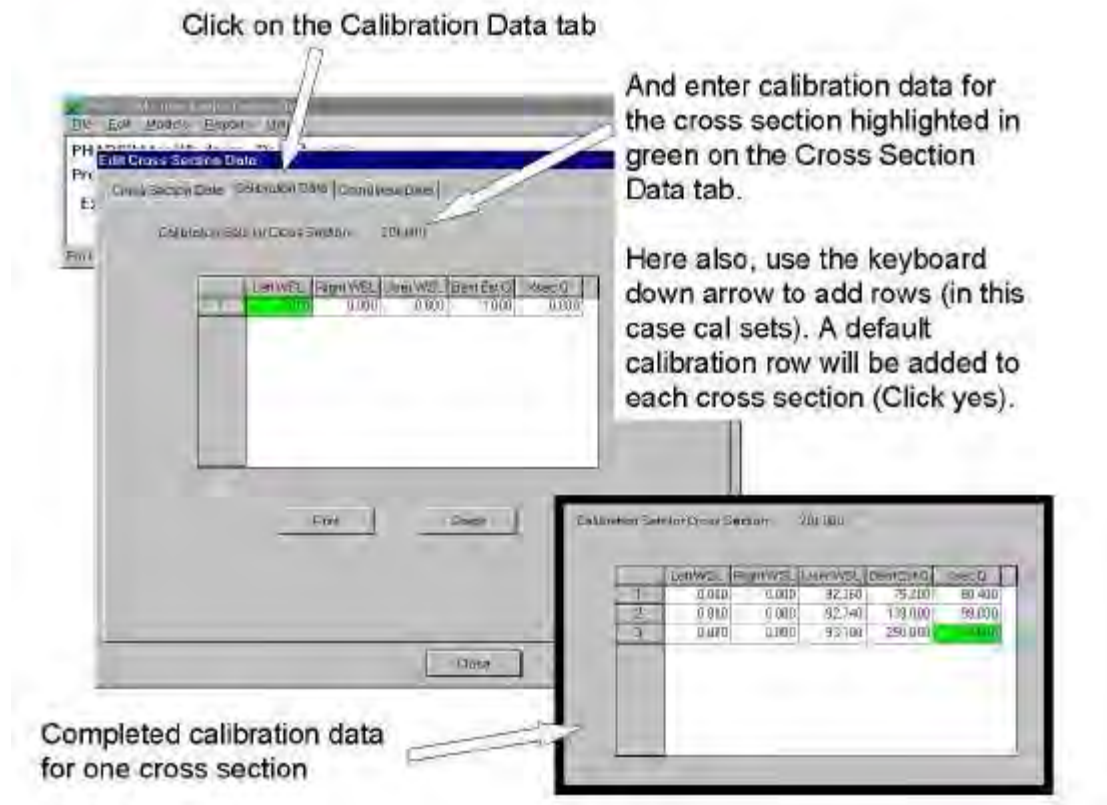


Figure L2-6. Entering calibration data.

Coordinate Data tab. Here you will find a difference from historical PHABSIM data entry in that there are values for X, Y, and Z. The inclusion of three dimensions is in anticipation of the ability to import GIS or spatially referenced data in the future. For now, enter the total distance upstream from the first transect as Y. Thus, X represents distance across the transect from the head pin, Y represents the distance upstream from the first transect (also referred to as Stationing), and Z represents the vertical distance above the datum selected for the study site. The program calculates Y values and those cells have a gray background.

From the data in sheet xsec01 enter the x-distance in column X, the distance upstream from the first transect in column Y, and the elevation in column Z. Channel index and individual Manning's n values for each cell are entered in the columns labeled CI and N. Calibration velocity sets are entered in the **Vel @discharge** columns. Enter the coordinate and velocity data from Table L2-1. The coordinate data entry process is shown in Figure L2

7. When you have finished, proceed to the **..Cross Section Data** tab, select the next cross section and repeat the Calibration Data and Coordinate Data entry steps.

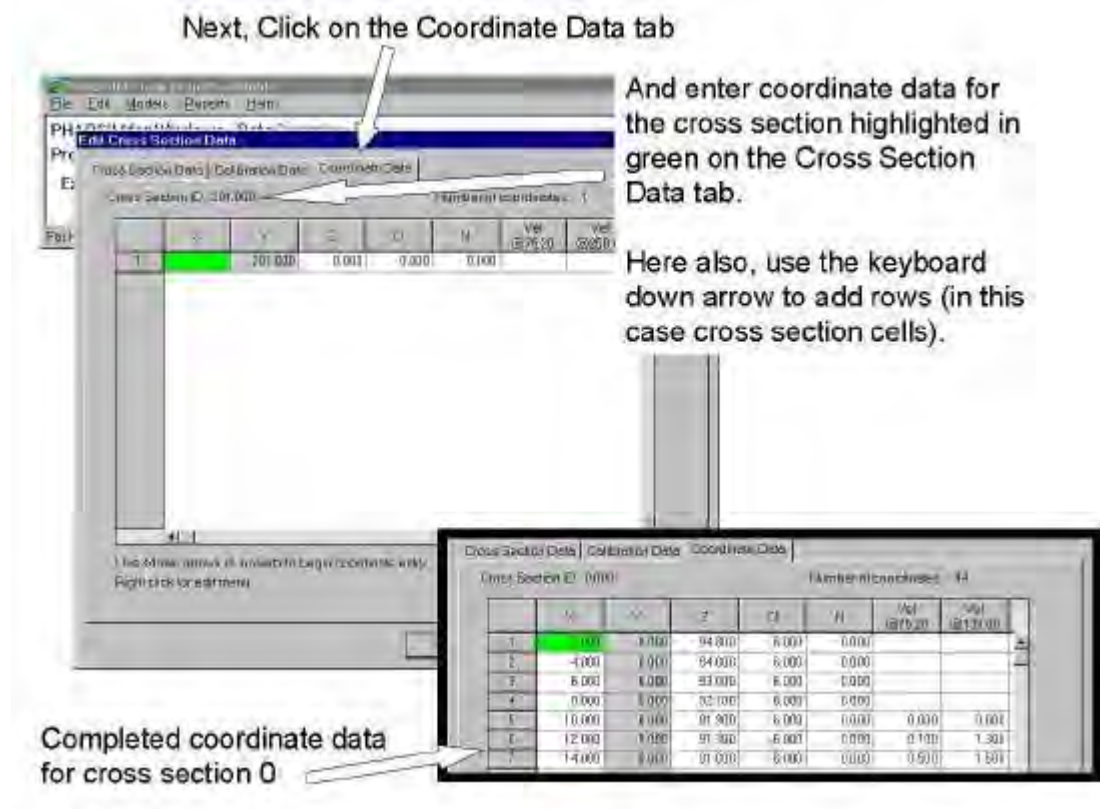


Figure L2-7. Coordinate data entry.

These steps would normally be repeated for all transects in the study. At that point, you have entered the basic hydraulic data for the study site. In this lab, we will also learn how to input coordinate data from a spreadsheet using Windows copy and paste functions for the third and fourth cross sections in this project.

Entering Coordinate Data by Copy and Paste from a Spreadsheet

PHABSIM for Windows allows entry of certain parts of the project data using Windows copy and paste operations. The third party data entry software has some quirks that must be accommodated to enable the copy and paste features. The next steps demonstrate how to paste coordinate data from a spreadsheet into PHABSIM for Windows.

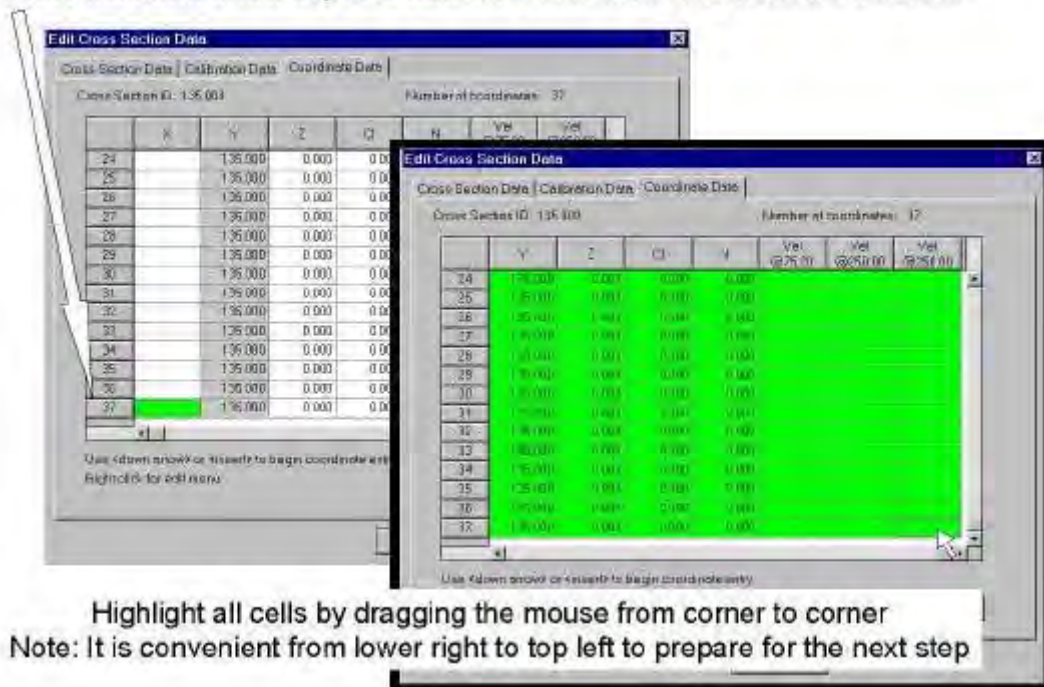
Move to the **Calibration Data** tab for cross section 135. Enter (type) the calibration data contained in Table L2-1. Now move to the **Coordinate Data** tab for cross section 135.

Start your spreadsheet software and open the spreadsheet named Mylab02.xls. Move to the worksheet labeled XSEC135. There you will find a block of cells containing the X, Y, Z, channel index, Manning's n, and calibration velocity data for this cross section. Using the row index at the left, determine the number of rows of data in the transect. Highlight this block of cells and execute the Windows Copy command to copy those values into the Windows clipboard.

Return to PHABSIM for Windows using a mouse click in that window.

Using the **Insert** or **Down Arrow** key, insert the number of rows of data (not row numbers) found in the **Coordinate Data** tab worksheet. (If you insert too many rows, right click and select **Remove Row** as many times as needed. Then, using the left mouse button, **Drag** the cursor from the lower left (last X, last vel) corner of the worksheet to the upper left, being sure to include the calibration velocity set columns. That entire area should now be highlighted. Next, **Right Click** and select **Fill** from the pop-up menu. The entire area will be filled with 0.00. Finally, move to the upper left corner of the coordinate data entry area again. **Right Click**, and select **Paste** from the pop-up menu. The highlighted coordinate data area will be filled with the data from the spreadsheet. This process is shown in Figures L2-8 through

Press the down arrow key until sufficient coordinate data rows are inserted

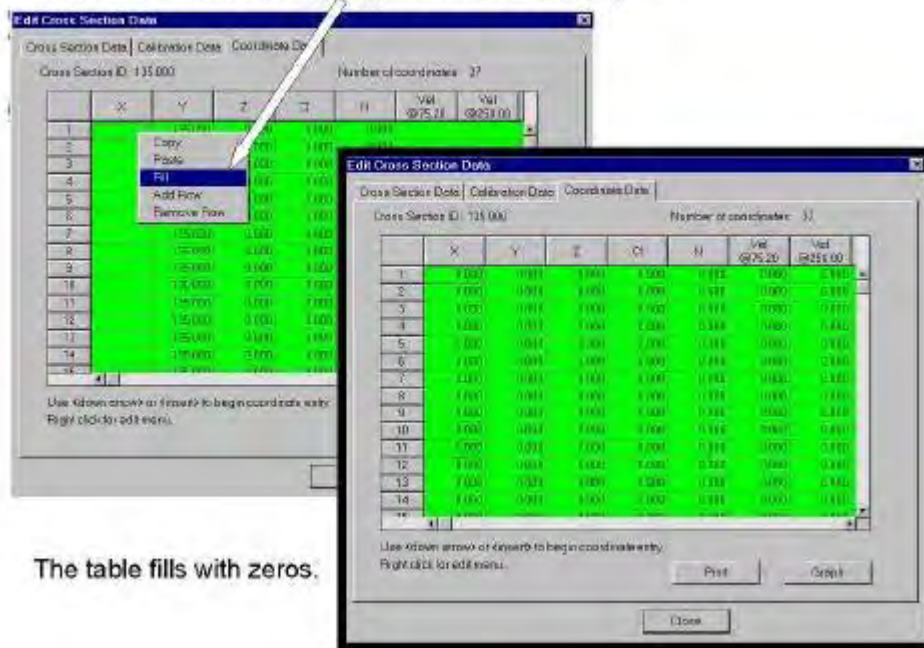


L2-10.

Figure L2-8. Opening and blocking coordinate data tab rows.

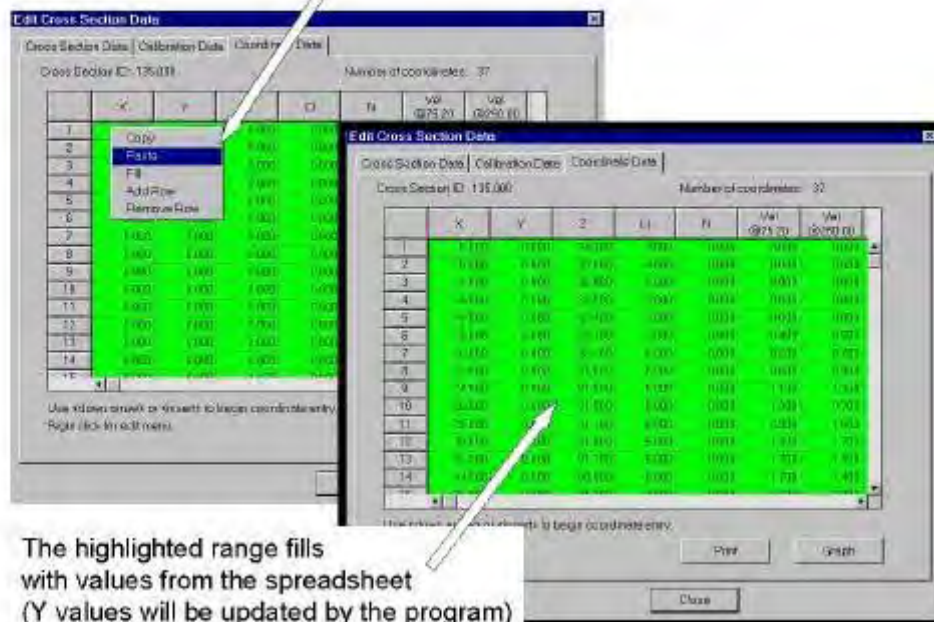
Due to the nature of the data entry grid software, calibration velocity cells that were blank in the spreadsheet now have zeros. Delete those zeros using the **Delete** key so the data set follows the convention that a blank velocity means the cell was dry and a velocity of 0.0 means the cell had standing water. Compare the PHABSIM for Windows data entry sheet with Mylab02.xls to ensure all of the required velocity cells are changed to blank. Column Y may change during this cut and paste operation, but it will revert to the calculated value the next time you open this tab.

Fill all cells with zeros using: Right Click and selecting Fill



The table fills with zeros.

Block and copy the coordinate data from your spreadsheet, Move to cell X1, Right Click and select Paste



The highlighted range fills with values from the spreadsheet (Y values will be updated by the program)

Figure L2-9. Filling the coordinate data table with zeros.

Figure L2-10. Pasting coordinate data from a spreadsheet.

Repeat these operations (Calibration and Coordinate Data) for cross section 201.

Step 3. Enter Suitability Data for Lab02

Click **\Edit\Suitability Curves** and you are presented with a dialog box where habitat suitability of use curve (HSC) data can be entered for all species of interest for the study. Begin by using **..\Suitability Curves\Edit\Add Curve** and entering the curve ID number and the species and life stage descriptions from the HSC sheet in the Mylab02 spreadsheet in the boxes provided. Note that curve ID numbers should be five or more digits to capture species and life stage coding. Then click **OK**. A table for entry of the Velocity curve information is displayed by default.

The same **Insert** key convention to create a new line used with coordinate data entry applies. You may also copy and paste HSC curves into PHABSIM for Windows using the conventions described for coordinate data above. You must type the species, life stage, and HSC number, but the coordinate data can be entered using copy/paste operations.

Enter the HSC data for velocity by copy and paste or by typing.

To switch to the Depth, Channel Index, or Temperature HSC curves, click the appropriate button in the Curve Type box at the upper right and enter the HSC data by paste or typing as above.

Repeat this process beginning with **..\Add Curve** for all HSC curve sets in the HSC sheet.

Enter Simulation Discharges for Lab01

This step may be performed now or after the hydraulic models have been calibrated. To avoid excessive output during the calibration process, the user would typically select to run the full range of simulation discharges toward the end of the hydraulic model calibration process. Those selections will be made in the WSL and Velsim windows in later lab exercises. We will enter a small number of additional discharges here to illustrate the process.

Select **\Edit\Discharges** to display the Simulation Discharges window. The user-defined calibration best estimated discharges (75.2, 139.0, and 250.0 cfs) are shaded in gray. They are automatically entered in the Discharge column. Note that they are marked “cal” in the Type column. Click on the first of these discharges and press the **Insert** key. A new cell with a value of 0.00 will appear. Enter a value of 15.0. Repeat this process with Insert (before the calibration discharges) or the Down arrow (after one or more calibration discharges) to enter the values of 60.0, 625.0, and 1250.0. Click the Close button to end discharge data entry.

You have now finished the basic data entry process. Save your project using **\File\Save Project**.

One more key data entry step remains, that of entering Suitability-of-use criteria (SI curves). This topic will be covered in Laboratory 7.

Step 4. Evaluate Diagnostic Plots

The quality of any modeling exercise begins with correct data entry. PHABSIM for Windows contains several means of viewing plots of the entered data for quality control. A longitudinal plot of the observed water surface elevations can be obtained using **\Reports\Graphs\Longitudinal Profile** and checking the Observed WSL box. Selecting **\Edit\Cross Sections\Coordinate Data** and clicking the graph button can view cross section geometry plots. The cross section profile is displayed for the cross section currently selected in **\Edit\Cross Sections\Cross Section Data**. To view different cross sections, return to the **..\Cross Section Data** tab and select the desired cross section, then return to the **..\Coordinate Data** tab. Combined plots of velocities, water surface elevations and bed geometry can be obtained using **\Reports\Graphs\Bed Profile with WSL\Velocities** and checking the Observed WSL and Observed Velocity boxes. You may wish to toggle on or off various calibration discharges for clarity.

Step 5. Quality Assurance

As noted earlier, a longitudinal plot of the observed water surface elevations can be obtained using **\Reports\Graphs\Longitudinal Profile** and checking the Observed WSL box. Cross section geometry plots can be obtained by selecting **\Reports\Graphs\Bed Profile with WSL\Velocities** and checking the Observed WSL and Observed Velocity boxes.

First, look at the longitudinal profile using **\Reports\Graphs\Longitudinal Profile**, and then the cross section profiles for each transect using **\Reports\Graphs\Bed Profile with WSL\Velocities**. In the cross section profile plots, select the cross section and discharge to be viewed in the tables to the left of the plot and click **Refresh**. Examining the longitudinal profile of the water surface elevations and thalweg depths in conjunction with the cross section profiles for these data should indicate cross section 0.0 is a riffle (or channel control) and that cross section 201 is in a pool. This is shown by the increased depths at cross section 201 (see longitudinal profile) as well as the more parabolic shape of the cross section profile at station 201.

Note in Table L2-1, the velocity values at verticals from 1.0 to 4.0 and vertical 44 have been left blank, since these verticals were out of the water at each of the calibration discharges.

In general it is a good idea to examine the longitudinal and cross section plots and note any areas that appear unusual. Are there any characteristics of this data set that merit further attention? **Hint:** look at the three velocity profiles for cross section 201. Look carefully at the shape of the velocity profiles and at the stream margins. Do you see anything that does not make sense? Are the longitudinal water surface profiles (look at longitudinal plot) consistent? If there are any questions, you can refer to the original field notes, consult with the crew members or look for other means (assistance of a hydraulic engineer or hydrologist, for example) to resolve inconsistencies.

Table L2-1. Data for cross section 0.0. **Table L2-1.** Concluded. **Table L2-2.** Data for cross section 60.0.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Distributed Parameter Models

Effective Habitat Analysis in PHABSIM

Interpreting PHABSIM and Completing the IFIM Process

Use of the PHABSIM for Windows Menu System

PHABSIM for Windows File Structure

Analysis Limits in PHABSIM for Windows

Summary of Chapter 1

Chapter 2, Hydraulic Modeling in PHABSIM

25

Objectives

Laboratories

Introduction

Terms and Definitions of Open-Channel Flow

Equations Used for the Description of Open-Channel Flow

Continuity and Mass Balance

PHABSIM FOR WINDOWS

vii

Union Analysis

Table L-2. Concluded.

Windows	DOS	Difference	% difference
Window elevation	91.65	0.00	0.00
Water surface elevation	91.486	-0.164	-0.18
Center channel elevation	91.65	0.00	0.00
Bed elevation	91.65	0.00	0.00
Water surface elevation	92.456	0.806	0.87
Water surface elevation	92.456	0.806	0.87
Depth Suitability Index	0.0068	0.0026	0.25
Depth Suitability Index	0.0068	0.0026	0.25
Combined Suitability Index	0.0068	0.0026	0.25
Weighted Suitable Area	8.698	11.79	135.56
Weighted Suitable Area	8.698	11.79	135.56

vii

Table L2-3. Data for cross section 135.0.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Distributed Parameter Models

Effective Habitat Analysis in PHABSIM

Interpreting PHABSIM and Completing the IFIM Process

Use of the PHABSIM for Windows Menu System

PHABSIM for Windows File Structure

Analysis Limits in PHABSIM for Windows

Summary of Chapter 1

Chapter 2, Hydraulic Modeling in PHABSIM

25

Objectives

Laboratories

Introduction

Terms and Definitions of Open-Channel Flow

Equations Used for the Description of Open-Channel Flow

Continuity and Mass Balance

PHABSIM FOR WINDOWS

vii

Table L-3. Concluded.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25
Acknowledgements				i
PREFACE				ii
A Brief History of PHABSIM				
Use of this Document				
Changes Between PHABSIM Version 2 and PHABSIM for Windows				
Conventions Used in this Document				
Chapter 1, Introduction to the Physical Habitat Simulation System				1
Objectives				
Associated Laboratory Exercises				
An Overview of IFIM				

Table L2-4. Data for cross section 201.0. **Table L2-4.** Concluded.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0.00	0.00
Water surface elevation	92.456	92.45	0.014	0.02
Water surface elevation	92.856	92.87	0.014	0.02
Depth Suitability Index	0.8968	0.896	0.014	16.15
Depth Suitability Index	0.0648	0.086	0.023	26.25
Combined Suitability Index	0.0644	0.089	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

APPENDICES

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hydraulic Modeling

Water Surface Elevation Modeling

Velocity Modeling

Habitat Modeling

The Average Parameter Model

Distributed Parameter Models

Effective Habitat Analysis in PHABSIM

Interpreting PHABSIM and Completing the IFIM Process

Use of the PHABSIM for Windows Menu System

PHABSIM for Windows File Structure

Analysis Limits in PHABSIM for Windows

Summary of Chapter 1

Chapter 2, Hydraulic Modeling in PHABSIM

25

Objectives

Laboratories

Introduction

Terms and Definitions of Open-Channel Flow

Equations Used for the Description of Open-Channel Flow

Laboratory 3. Water Surface Modeling Using A Stage-Discharge Approach

Objective

The objective of this laboratory is to demonstrate modeling water surface elevations based on a stage-discharge regression approach. The reader will be introduced to the use of the STGQ program within PHABSIM for this purpose. The general theory of stage-discharge modeling using a regression approach is covered in the manual in Chapter 3.

Program Used: STGQ

Project File Used: C:\My Documents\Phabsim\Laboratories\Lab3.phb

Introduction

The purpose of this laboratory is to introduce stage-discharge regression modeling in PHABSIM using the STGQ model. Recall from the lecture material that under most circumstances an investigator will obtain measured water surface elevations at a specific cross section at three or more flows, which is illustrated in Figure L3-1 for cross section 0.0 for the Fryingpan River (see Laboratory 1 or access \Models\WSL\STGQ Options\Stage Discharge Graph in the Lab3 project).

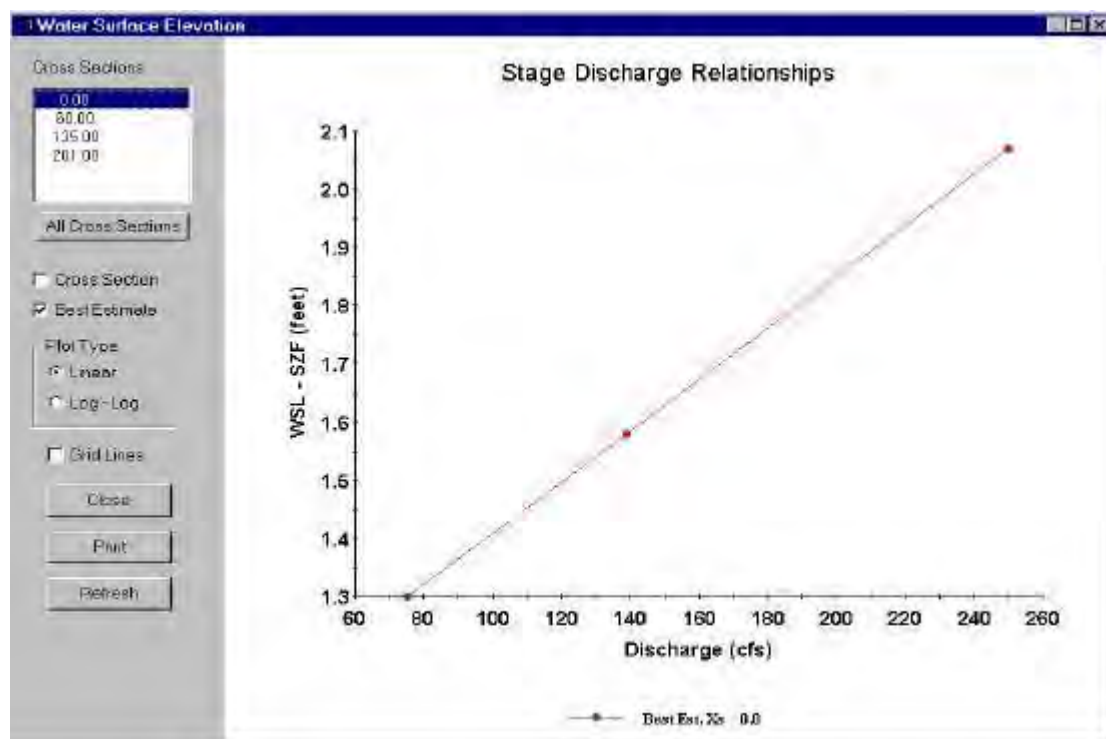


Figure L3-1. A stage-discharge relationship.

As discussed in Chapter 3, the relationship between stage (i.e. water surface elevation) and discharge can often be represented at a cross section in a channel by the following equation:

$$(WSL - SZF) = a Q^b \quad (L3-1)$$

where: Q = discharge

WSL = stage or water surface elevation

SZF = stage of zero flow

a = constant derived from measured values of discharge and stage

b = coefficient derived from measured values of discharge and stage

Note that the SZF is included in Equation L3-1 since the stage-discharge relationship at a channel cross section is a function of the SZF at that specific location as discussed in Chapter 3. The SZF is used within the STGQ program and should be included whenever using alternative stage-discharge regressions. Equation L3-1 can be transformed to a linear relationship between stage and discharge by taking the $\log_{10}$ of the equation, which yields:

$$\log_{10} (WSL - SZF) = \log_{10}(a) + b * \log_{10} (Q) \quad (L3-2)$$

Given at least three sets of measured stage-discharge data at a cross section, a simple linear regression can then be performed using Equation L3-2 to determine the constant and coefficient and the resulting regression equation can be used to predict stage over a desired range of discharges. The effectiveness of this modeling approach for the simulation of water surface elevations is not only a function of the observed data, but also the channel geometry and relative difference in the slopes of the regression lines between adjacent cross sections (see Chapter 3 of the manual).

In regression-based modeling, the primary modeling choices involve the selection of the appropriate calibration discharges (i.e., best estimate of discharge versus cross section specific [or “local”] discharges), determination of an appropriate SZF, and selection of the calibration water surface elevations. In this laboratory, the best estimate of the discharge and average water surface elevations will be used in the regressions. The SZF has also been determined based on the thalweg bed elevations at each cross section following the procedure outlined in Chapter 3 of the Manual.

Figure L3-2 contains the log of the water surface elevations (minus SZF) versus the log of the discharges (best estimate) for all four of the cross sections for the Fryingpan River. This figure is provided to assist in an understanding of the laboratory data and in the interpretation of the laboratory results.

Now proceed through the laboratory steps in the given order.

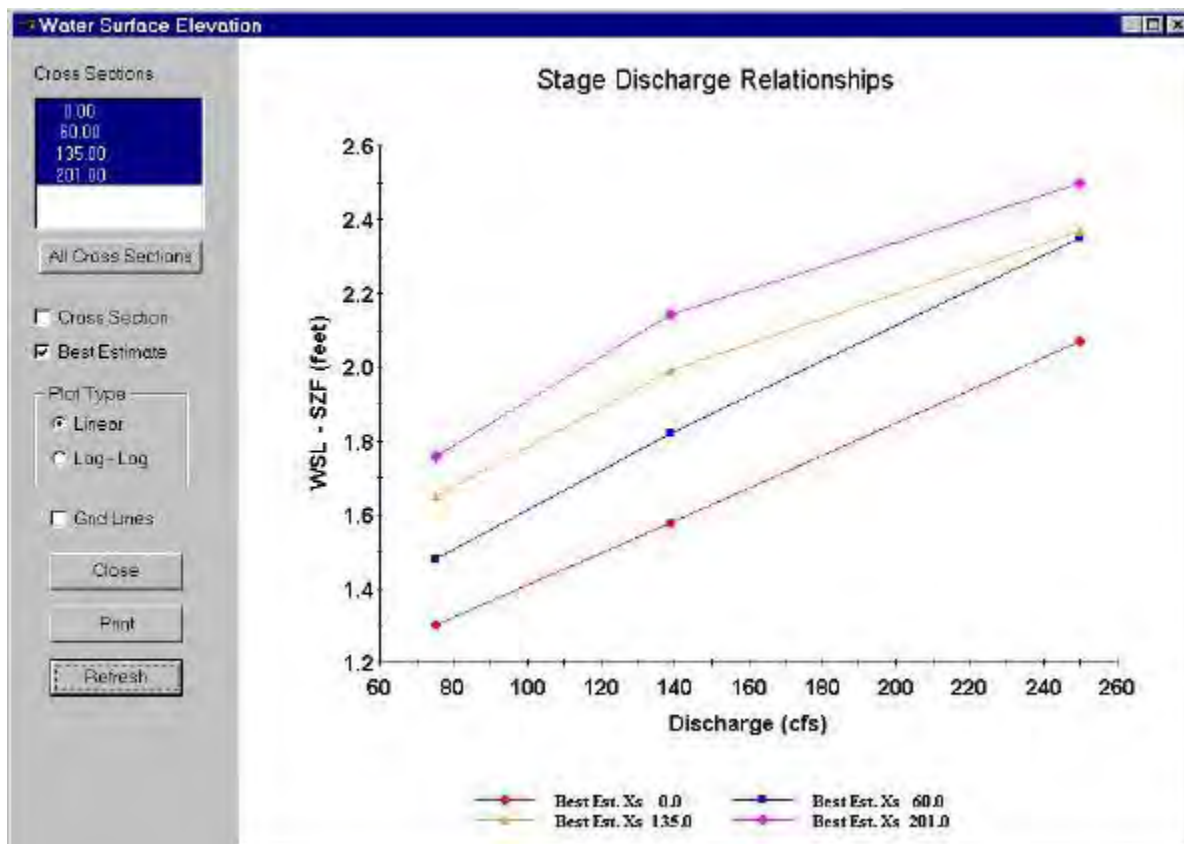


Figure L3-2. Stage-discharge relationship for four cross sections.

Step 1. Selection and Setup of STGQ Water Surface Simulation Model

The complete project data set for the Fryingpan River is supplied with the PHABSIM distribution disks and is named SAMPLE1.phb.

Begin by starting PHABSIM and opening the SAMPLE1 project. Select **\Models\WSL**. The **Water Surface Elevation Simulation** window opens and the **Output Options** tab is displayed by default. In this window the user can select which of the discharges supplied earlier are to be used at the current stage of the simulation process. For example, while calibrating the hydraulic models, it is suggested to use only the calibration discharges. Thus, the check boxes in the **Use** column should be toggled so only the “cal” discharges are checked. When doing a final production run, all discharges would be checked. In this lab, we are running a small number of discharges, so leave this set at **Use All**.

In this window, you may also choose to overwrite the ZOUT (results output) files. If you chose not to overwrite ZOUT, successive runs of the models in PHABSIM append their results to ZOUT. This can result in a very large file, but may be necessary when working on a particularly difficult simulation. You may select **Overwrite ZOUT File** for this lab by clicking on the box or the **Overwrite ZOUT File** text so a check mark appears.

Next, click on the **STGQ Options** tab. Examine the options (see Chapter 3) and make sure that you understand which options are being used. In particular, note the Discharge (IOC Option 5) has been set to “Best Est Q” for all calibration sets for all transects. This instructs STGQ to use the first “best-estimate” discharge in the stage-discharge regressions. Setting the items in the Discharge column to **Xsec Q** will use the discharge measured at that cross section in the stage-discharge regression. This is not necessarily equivalent to the best estimated discharge for the reach at that calibration flow, but may provide a better fit to the observed water surface elevation for individual cross sections under some conditions.

Also note that the project has seven simulation flows ranging from 15.0 to 1250.0 cfs, which represent a range of discharges both lower and higher than the three calibration, flows of 75.2, 139.0, and 250.0 (see Laboratory 1). The higher and lower discharges allow an evaluation of model performance over a simulated range of discharges that is needed for the final habitat-discharge relation.

Step 2. Obtain the Calibration Water Surface Elevation and Discharge Data

Select **Edit\Cross Sections\Calibration Data** to find the calibration data sets for the first cross section (i.e., cross section 0.0) and note the three calibration flows and their observed water surface elevations.

The three calibration flows (best estimate of discharge as well as the actual measured discharge at this cross section for each calibration set) and the corresponding water surface elevations from the CAL lines are:

Find and record the water surface elevations, discharges, and SZF for all cross sections in Table L3-1 by first clicking on the **Cross Section Data** tab, and on the **Windows** tab, then the **Calibration Data** tab. Once you have recorded the data in Table L3-1, choose cancel and return to the **Models\WSL\STGQ Options** tab.

Table L3-1. Calibration information for the Fryingpan River.

In this example, the best estimate of the discharge was determined from an examination of the measured

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

PREFACE

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

Objectives

Associated Laboratory Exercises

LABORATORY 3 – WATER SURFACE MODELING USING A
STAGE-DISCHARGE APPROACH

i

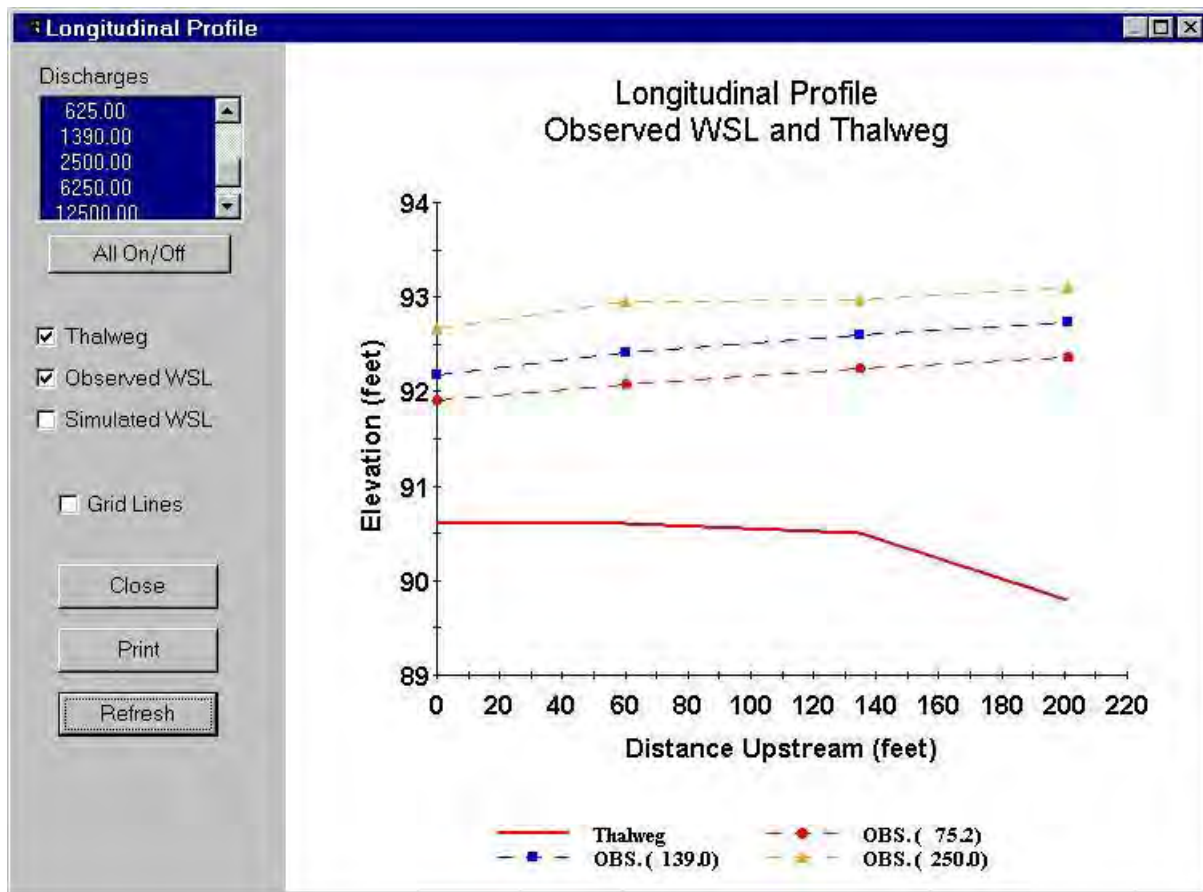
ii

1

discharges at each cross section. In some applications, the best estimate of the discharge could have been derived from a gage within the reach or from the average of a selected number of the measured transects where conditions for obtaining good flow estimates was possible.

Step 3. Examination of the Stage-Discharge Relationships

The summary data in Table L3-1 was used to create a plot of the observed longitudinal water surface elevations versus discharge for the calibration data and a plot of the log of the discharge versus the log of the (WSL-SZF) (see Figures



L3-1 and L3-2).

Figure L3-3. Observed water surface profiles.

First, it should be apparent from the plot of the longitudinal profile of the calibration data (Figure L3-3) that at the high calibration flow, a flattening of the water surface elevation is apparent at the middle two cross sections. This may be indicative of a backwater effect at this discharge. Although backwater effects can be pronounced more often at low flows due to riffle type habitats, channel constrictions can produce this effect at higher discharges. We do not know (since we did not collect this data) what is actually occurring.

Examining the plot of the log-log relationship between WSL-SZF and discharge shows that the observed data for cross sections 60 and 135 have almost identical WSL values at the high calibration discharge (see Figure L3-2). This should

indicate that using a regression approach (i.e., stage-discharge with STGQ) may be problematic at high simulated discharges since the regression lines will likely >cross over= each other. This will be explored in more detail in this laboratory.

Step 4. Running the Stage-Discharge Regression

Running the STGQ model to perform stage-discharge regression modeling is basically an automated process once the appropriate data have been entered and model options have been selected.

Select **\Models\WSL\STGQ Options** and ensure that the SZF box is checked for each cal set for each transect (the default). In rare instances removing the check mark can be used to set the SZF used in the calculations to zero. You will not encounter such a situation in this class. Click the **Write Computational Details** check box so the program produces a file called ZOUT containing the computational results. Once you have experience with PHABSIM, this file can be omitted during the calibration process. It is often a good idea to turn on this option when doing production runs in case an “at the time” record is needed for documenting or defending the study.

Next click the **Assign Cal Sets** button. Select each transect using the dialog box in the upper left and ensure that there is a check for each cal set for each applicable discharge. Selecting **All On** means that the WSL for all discharges will be simulated using all cal sets in the regression model. Under various circumstances of data quality or channel configuration it may be desirable to use only a portion of the available cal sets for a given discharge at a particular cross section. Note: you may have more than three Cal sets, but only certain ones may apply to specific cross sections. That selection is made in the **Assign Cal Sets** table.

In PHABSIM for Windows it is possible to use different water surface elevation models for different transects at different discharges. Therefore, you must specify which model is being used for each transect/discharge combination. Clicking the Method tab and selecting a method from the list on the right and clicking the appropriate position in the cross section discharge table accomplish this. For this laboratory exercise, click **STGQ** and then click **Set All**. This tells PHABSIM for Windows that the STGQ model will be applied to all combinations.

Now you are ready to run the STGQ program. Simply click the **Run** button at the bottom right. When the model has finished running a “WSL Simulation Completed” message will be displayed. To view the results, click **OK** and then click the **Results** tab.

In the **Results** tab window you will see a table of water surface elevations for each transect – discharge combination. Plots of the water surface elevation results can be viewed by clicking either the **Cross Section** or **Longitudinal** buttons at the bottom.

Step 5. Evaluation of the Stage-Discharge Model Results

At this point, we are interested in determining how well the regression approach is working as a model for use in simulations of water surface elevations. Figure L3-4 contains simulated water surface profiles derived from the stage-discharge relations for the four cross sections.

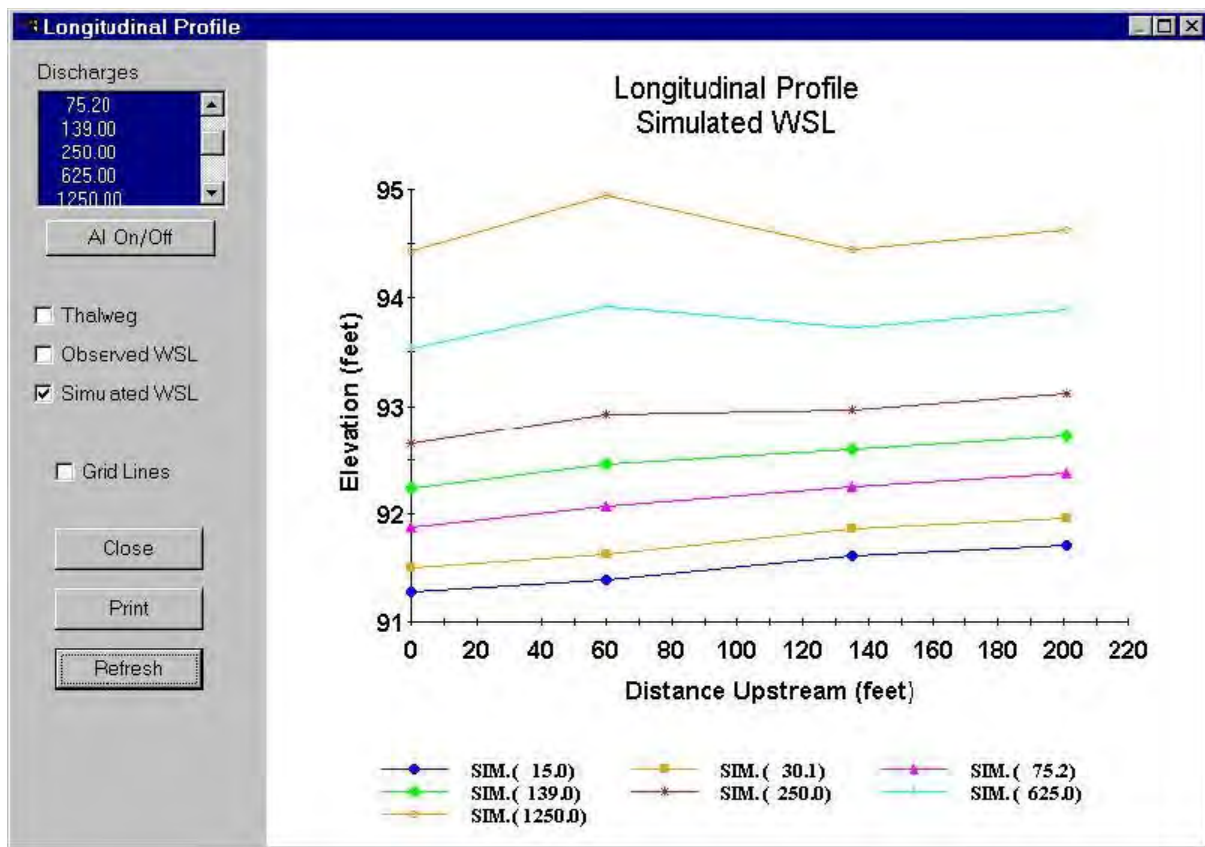


Figure L3-4. Water surface profiles simulated with STGQ.

Click the **Longitudinal** button to view a plot of the water surface profiles for each discharge as simulated by STGQ. Remove checks from the Thalweg and Observed WSL boxes to arrive at Figure L3-4. The top line in this graph (i.e., labeled SIM.(1250.0)) represents the predicted water surface elevation at a discharge of 1,250 cfs. The predicted water surface elevations at each cross section are derived from each cross section's regression equation based on the three sets of calibration data. At this discharge, water appears to be flowing downhill from right to left in this figure. Note that at 1,250 and 625 cfs, water is >flowing uphill= from cross section 135 to 60. These results are irrational from a physical standpoint and indicate that the regression models are not appropriate at higher discharges for this data set. In reviewing the simulation results for **1250.0** cfs, it should be apparent that the >water flowing uphill= between cross section 135 and 60 is >worse= than that observed at 625 cfs. This suggests that the further you extrapolate above the highest observed discharge (250 cfs) the more error in estimated water surface elevation you will have.

At this point, we only know that somewhere between 250 and 625 cfs, the stage-discharge regression approach >breaks down=. If we wanted to better define where the model no longer works properly, we could add additional QARD flows to our data set, such as 275, 300, 325, etc., up to 625 and rerun the STGQ model. Examination of the output would show the specific flow range at which water begins to >run uphill=.

Based on our examination of the plotted longitudinal profiles and the previous examination of the observed calibration data we can more easily understand how these irrational results can be generated by the regression modeling approach.

The STGQ program performs the regression analysis at each cross section independently. Although the r^2 for the regressions at each cross section are > 0.99 , the difference in slope for each regression equation results in predicted water surface elevations which **cross** at simulated discharges just above the highest calibration flow. This should be expected given the observed relationships between discharge and water surface elevations shown in Figure L3-2, where the observed water surface elevations at cross sections 60.0 and 135.0 are very close and tend to **>converge=** over the range of observed discharges.

The modeling results would indicate that the stage-discharge modeling approach may be valid at simulated discharges up to our highest measured data (i.e., 250 cfs) but that an alternative modeling approach for higher simulated flows will be needed. In Laboratory 4, the MANSQ model will be used, while Laboratory 5 will employ the WSP model to deal with this phenomena.

Step 6. Explore STGQ Regression Modeling Options

This section of the laboratory is optional and intended to be completed at your convenience.

As indicated previously in the laboratory, the user can select which of the cal set discharges to use in the regression modeling with STGQ. In the previous laboratory steps, the stage-discharge regressions were conducted using the best estimate of the discharge by setting the **Discharge (IOC 5)** column to **>Best Est Q'** for all cross sections and cal sets. This forced STGQ to use the best estimate of the discharge in the regression computations. In this step of the laboratory, we will set these values to **"Xsec Q"** so that the regressions are performed using the calculated discharges at each cross section at each calibration flow.

If you are not in the **\Models\WSL** window, move there now. Click the **STGQ Options** tab and click on the first entry **"Best Est Q"**. Next, click on the small wedge arrow  to the right of the cell and then click **"Xsec Q"**. Repeat this for all cal sets for all transects.

To ensure the PHABSIM for Windows interface recognized the change, go to the **Methods** tab and then click **STGQ** and click any one of the transect – discharge cells to ensure the **Apply** button becomes active. Then click the **Apply** button and view results as before.

What you should find is that the **>error=** values in the regression equations have remained the same or increased and that regression modeling of these data with discharges measured at each cross section instead of a best estimate of discharge does not eliminate the irrational results of simulated water surface elevations at flows higher than our high flow calibration data set. Using the computed discharges for each cross section can, and often will, result in poorer linear relationships using Equation L3-2. This type of variability between cross sections using computed discharges is not atypical when field data has been collected in a variety of fisheries habitats which are poor in terms of obtaining a **>best estimate=** of the discharge for hydraulic modeling.

As a final wrap-up to this laboratory, go to the **STGQ** tab and reset all of the discharges to **Best Est Q**. Then go to the **Methods** tab, ensure that **STGQ** is marked and click **Select All**. Click **Run**, go to results, and view the longitudinal plot. Zoom on the calibration discharges (hold Shift and drag a box with the mouse and release the mouse button) and print the plot for later reference.

Laboratory 4. Water Surface Modeling Using the MANSQ Model

Objective

The objective of this laboratory is to demonstrate the technique of modeling water surface elevations based on using Manning's equation (i.e., the MANSQ model). The general theory for the MANSQ program is covered in the manual within Chapter 2.

Programs Used: MANSQ

Project Files Used: Lab4.phb

Introduction

The MANSQ model can be used to simulate the stage-discharge relationship for individual cross sections. The model assumes that flow variations caused by changes in channel configuration are negligible (i.e., minimal backwater effects). The application of the MANSQ model in pools can be problematic since pools are generally created by backwater effects of a downstream hydraulic control. The MANSQ model assumes that each cross section is independent of all other cross sections during calibration and simulations. Therefore, the longitudinal profile of the simulated water surface elevations should always be checked to assess overall model performance.

At a computational level, the MANSQ model uses Manning's equation in the form:

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \quad (L4-1)$$

□□

$$\equiv n \downarrow$$

which is simplified to:

$$Q = K A R^{2/3} \quad (L4-2)$$

The value of K is determined from a single measured discharge-water surface elevation data set and the measured channel geometry at a cross section. The program then uses additional calibration data sets (i.e. discharges and water surface elevations) to solve one of the following two equations selected by the user:

$$K = K_o \left(\frac{Q}{Q_o} \right)^b \quad (L4-3)$$

$$K = K_o \left(\frac{R}{R_o} \right)^b \quad (L4-4) \leq R_o \leq$$

where: subscript $\geq o$ refers to calibration values **b** is a coefficient supplied by the user for each cross section

LABORATORY 4 – WATER SURFACE MODELING USING THE MANSQ MODEL

Calibration of the model is accomplished by selecting an initial calibration discharge to compute K_o , and then employing a trial and error procedure for selecting a value of b that minimizes the error between observed and predicted water surface elevations for the remaining calibration data sets. Typical values of b range from 0.0 to 0.6 in most channels and as noted in Chapter 2. The steps in this laboratory represent a suggested order for MANSQ analysis.

Step 1. Obtain an Initial Estimate of b

Begin by initially setting that the b value for each transect in **\Edit\Cross Sections\Cross Section Data** to 0.2. This is an arbitrary default value derived from taking the median value for a large number of study sites. Final b values will be determined by observing the results of simulating water surface elevations with MANSQ.

In this step, the CALCF4 program will be used to obtain an initial estimate of b . Run the CALCF4 program by clicking **\Models\CALCF4**. The results will be automatically displayed to the screen. Scroll down the file and locate the conveyance factor (CFAC) regression equation for cross section 0.0. Alternatively, use the Notepad editor to search for "CFAC" in the current ZOUTx file.

The exponent of the CFAC regression equation represents an excellent initial estimate for b and is -0.003 for cross section 0.0. Continue through the output listing to locate and record the CFAC regression exponents at the three remaining cross sections. Record these values in Table L4-1.

Note that the CFAC regression exponent at cross section 0.0 is negative. Under most circumstances, the use of negative b values is not expected since this would imply that roughness would be increasing with discharge. In typical applications of MANSQ, a negative b would be rounded up to 0.0 for use in the model.

Table L4-1. CFAC regression exponents for		Windows	
Once the remaining CFAC exponents have been entered in Table L4-1, exit Notepad if you have been using it to find the CFAC exponents and return to \Models\WSL\MANSQ in PHABSIM for Windows.	Cell bed elevation	91.65	each cross section.
	Water surface elevation	92.456	
	Depth	0.806	
	Depth Suitability Index	0.0708	
	Combined Suitability Index	0.0644	
	Weighted Usable Area	8.698	

The MANSQ program requires a calibration flow and water surface elevation at each cross section in addition to the initial estimate of b . These data are derived from the calibration data sets entered in **\Edit\Cross Sections\Calibration Data** for each cross section. For this laboratory, the high flow calibration data at each cross section will be used as our initial calibration flow for MANSQ.

Table L4-2. Calibration discharges and water surface elevations for the Fryingpan River from MANSQ using 250 cfs (Cal Set 3) as the calibration discharge.

	Calibration Q	Cross section 0	Cross section 60	Cross section 135	Cross section 201
	75.2	91.90	92.08	92.25	92.36
	139	92.18	92.42	92.59	92.74
	250	92.67	95.95	92.97	93.10

NOTE: You may choose either the high, medium or low flow calibration data sets (or any combination for specific cross sections). However, selection of the calibration discharge should be considered of the flow ranges most critical to the study. Remember, MANSQ will >return= the observed water surface elevation at the calibration flow and the >error= between predicted and observed water surface elevations at the other calibration discharges will be a function of the field data and selection of appropriate **b**=s. We will select **b**=s to minimize the error between observed and predicted WSL at each transect.

Step 2. Running the MANSQ Model and Evaluating Results

Select the \Models\WSL\MANSQ tab and note the options available in the MANSQ program and review the options that have been set. For this laboratory exercise, the default options will suffice. However, advanced users may wish to consider the alternative ratios of flow conditions given in equations L4-3 and L4-4, and other MANSQ options.

Next, click on the **Methods** tab and click **MANSQ** followed by **Set All**. This assigns MANSQ as the model to be applied to all cross sections at all discharges. Now click **Run**.

Since we have chosen the high calibration flow (i.e., 250 cfs) MANSQ will always return the observed water surface elevations for this flow at each cross section. We need to evaluate the predicted water surface elevation at each cross section for the medium (139 cfs) and low (75.2) calibration flows.

The **Results** tab contains a table of predicted water surface at each of the simulated discharges for each cross section. Click the **Print** button to obtain a copy of this table for later use. Click the **Longitudinal** button to view a plot of the longitudinal profile for all discharges. Click the check boxes for **Observed WSL** and **Simulated WSL**. Note the wild divergence of the WSLs at transects 135 and 201. The steep water surface elevation at high flows is unrealistic for a pool. In addition, the water surface elevation at the lowest discharges runs uphill. Our initial **b** values are not working too well.

Compare the predicted water surface elevations at 139 cfs and 75.2 cfs for each cross section against the observed water surface elevations for these calibration flows. It is apparent that an initial estimate of **b** of 0.2 results in a prediction of the water surface elevations at cross sections 0 and 60 that are too low, while this same **b** results in a prediction of water surface elevations at cross sections 135 and 201 which are too high at the high discharges and too low at the low discharges.

This means that **b** coefficients at all cross sections need to be adjusted in order to obtain better agreement

LABORATORY 4
– WATER SURFACE MODELING

USING THE MANSQ MODEL

between observed and predicted water surface elevations. **Table**

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferability of Suitability Curves

Segmenting the Study Area and Study Site Location

Critical Reach

Mesohabitat Study Site Selection

Cross Section Selection and Field Data Collection

Cross Section Selection

Field Data Collection

Hvdraulic Modeling

L4-3. MANSQ calibration table.

Step 3. Trial and Error Calibration of MANSQ by Adjusting **b at Each Cross Section**

You have now obtained an initial solution of the water surface profile using MANSQ but some adjustment is needed. Return to **\Edit\Cross Sections** and change the **b** coefficient from 0.20 to 0.02. Make this same change to the **b** value at cross sections 60 to 201. Note that these new estimates of **b** have been entered in Table L4-3.

Click OK to exit Edit\Cross Sections and save the file changes. Return to **\Models\WSL\Methods**, check that the MANSQ method is selected, and click **Set All** again. When the program has finished, click **OK** and **Results** as before.

LABORATORY 4 – WATER SURFACE MODELING USING THE MANSQ MODEL

Compare the Results table displayed on the screen to the one you printed earlier. What happened to the predictions for the water surface elevations when we increased or decreased **b** at the cross sections?

You should find that increasing **b** will result in predicted water surface elevations which increase for discharges above the calibration discharge, while decreasing **b** results in the predicted water surface elevations decreasing. The opposite will be true below the calibration discharge.

Return to **\Edit\Cross Sections** and change the **b** values for each cross section to induce the needed change in WSL at each transect to match the calibration discharges. Record these values in Table L4-3. Remember to use a **b** value of 0.00 instead of negative values for any cross section. Save these changes and re-run the MANSQ program and record the new predictions for the water surface elevations at each cross section for the medium and low calibration flows in Table L4-3. How close are the predictions of water surface elevations?

Based on these results, make adjustments to the **b** values as necessary. Your strategy should be to minimize the error between predicted and observed WSLs at both the 139 cfs and 75.2 cfs calibration flows for each cross section (you cannot get them both to be exact) by selecting the 'best' **b** for each cross section. Remember, MANSQ treats each cross section independently, so if you get a particular cross section to work, you no longer have to adjust the **b** value at the cross section while continuing your calibration efforts at other cross sections. You should make several trial runs during the lab in your quest for the best fit; however, due to class time limitations, the final calibration **b** values are provided in Table L4-3.

Step 4. MANSQ Final Calibration Run and Hydraulic Diagnostics

Up to this point we have focused on the calibration discharges and have not dealt with the WSL for the other discharges in the data set. The particular **b** values entered at the far right in Table L4-3 generally result in a maximum error between observed and predicted water surface elevations at the calibration flows, which range between 0.00 and 0.06 feet. This magnitude of difference is on par with the results obtained from the stage-discharge regression approach covered in Laboratory 3. However, we still need to check the effectiveness of the hydraulic simulations further by looking at the longitudinal profile of the water surface elevations at all simulated discharges.

View the longitudinal plot in **\Models\WSL\Results** again. Expand to full screen using the Windows maximize button for the graph window. It is useful to print this graph and label it MANSQ final for later reference.

The thalweg depths for each cross section are displayed as the bottom line with the x-axis indicating the distance between each cross section moving in an upstream direction. The top line in this graph represents the water surface elevation at a discharge of 1250 cfs. Using the key at the bottom of the plot, the other discharges can be identified by their line and symbol combinations. To aid in viewing simulated water surface profiles only, the **Observed WSL** check box can be left blank (click to remove check).

The predicted water surface elevations at each cross section are derived from the MANSQ model based on the calibrated **b**'s. At this discharge, water appears to be flowing downhill for some cross sections and uphill for others.

Note that at the simulated discharge of 625 cfs, water is 'flowing uphill' between cross sections 3 and 2. Although excellent agreement can be obtained with MANSQ for the calibration data, the simulated water surface elevations at discharges greater than 250 cfs are irrational.

At this point, we know that somewhere between 250 and 625 cfs, the MANSQ model 'breaks down' in a similar fashion to the results obtained using the IFG4 model in Laboratory 3. The reason behind the production of LABORATORY 4 – WATER SURFACE MODELING

USING THE MANSQ MODEL

irrational results with MANSQ for this data is basically similar to the reasons discussed in Laboratory 3 using IFG4. In MANSQ, the **b** value represents the exponent in a power law relationship (see Equations L4-3 and L4-4) that approximately tracks the changes in Manning's *n* over a range of discharges. Therefore, **b** acts as the 'slope' factor for the relationship between water surface elevation and discharge. Since the measured water surface elevations at cross sections 60 and 135 are very similar at the high calibration flows (see Table L4-2), the 'best fit' relationship derived from matching the water surface elevations at the two lower calibration flows causes the predicted water surface elevations to cross over at simulated discharges above 250 cfs.

At this point, an alternative modeling approach for the simulation of discharges greater than our high flow calibration (i.e., 250 cfs) should be considered. Given the nature of these data, modeling options within MANSQ are not likely to improve the simulation results (i.e., use of Equation L4-4 rather than Equation L4-3). Given the results already examined in Laboratory 3 using IFG4, the WSP model would be the next step and is examined in Laboratory 5.

Laboratory 5. Water Surface Modeling Using the WSP Model

Objective

The objective of this laboratory is to demonstrate the technique of modeling water surface elevations based on the step-back water method as implemented in the WSP model. We will cover the steps of finding an overall

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0611	0.087	0.023	26.25

Manning's n value that is a "best fit" for the study site, adjusting n values to capture localized roughness differences at each transect, and specifying roughness modifiers to accommodate the change in n value as a function of discharge. The general theory for the WSP program is covered in the

Introduction

The WSP model is a water surface profile program that is used to predict how the longitudinal profile of the water surface elevation changes over a range of simulated discharges. The initial objective in the calibration of the model is to use a trial-and-error procedure to select Manning's n coefficients at each cross section, which will replicate the longitudinal profile of the water surface elevations at this single calibration flow. This requires that the bed geometry elevations and water surface elevations have been measured to a common benchmark or elevation datum (i.e., the cross sections are 'dependent' and connected). We first attempt to find a global value (or overall channel roughness value) for n that is applied at each cross section to produce a "least error fit" of the water surface elevation profile to the observed data for one discharge. We then vary Manning's n for each cross section (within reasonable limits) to achieve a reasonably close fit between observed and predicted water surface elevations. Finally, we use a trial-and-error procedure to select main channel and overbank roughness modifiers that produce the best fit between observed and predicted water surface profiles for all remaining calibration flows. The relationship between the calibrated roughness modifiers and discharge is then used to develop either a regression equation or a good linear approximation, from which we can estimate the appropriate roughness modifiers for all simulation discharges of interest.

WSP requires a starting water surface elevation or energy slope as an initial condition. We have already found stage-discharge relationships using a regression approach (i.e., STGQ) and by calibrating MANSQ for the downstream cross section. To provide WSP with the needed initial condition, the user selects the combination of starting conditions based on using the water surface elevation derived from STGQ or MANSQ in the **\Models\WSL\Methods** tab by clicking on **..\WSP\STGQ supplies initial WSL** or **..\WSP\MANSQ supplies initial WSL** or **..\WSP\User supplies initial WSL**. The two combined WSP\XX options take the starting water surface elevation from one of those models and supplies it to WSP. The WSP\User option allows the user to set this value manually. The **..\User supplies WSL (no model run)** option allows users to import WSL values for the entire study area and discharge range from an outside source.

In this laboratory, we will select the high flow calibration data as the starting point in the calibration of the WSP model. In particular, we are interested in determining if this modeling approach can overcome the problem with simulated water surface elevations at higher discharges encountered when using a stage-discharge regression (i.e., STGQ in Laboratory 3) or the MANSQ model (Laboratory 4). The laboratory also provides a discussion of the implications of using a different initial calibration flow and resulting impacts to simulated water surface elevations. The given steps represent a suggested order for WSP analysis.

Step 1. Prepare Data and Select Options to Run the WSP Program

We begin by setting the same initial Manning's n roughness value for all cross sections. Start PHABSIM for Windows and load Lab5.phb. Select **\Models\WSL\WSP Options** and note that a Manning's n value of 0.030 has been entered for all cross sections.

WSP requires that the water surface elevations at the down stream cross section for each discharge are supplied to the model as boundary conditions. For discharges of 75.2, 139, and 250 cfs we know the actual observed water surface elevations at the down stream most cross section (i.e., cross section 0.0). However, the water surface elevations for the remaining four discharges are not known. To resolve this issue, we use STGQ or MANSQ to obtain water surface elevations for the downstream cross section. From Labs 2 and 3 we know that STGQ produces a slightly better fit between observed and simulated water surface elevations at cross section 0. Thus, we will use STGQ as the source of starting water surface elevations.

Move to **\Models\WSL\Methods** and first select **WSP** (click the radio button) followed by **Set All**. This saves clicking on each element of the table separately. Now select the **..WSP\STGQ** radio button and click in the cross section 0.0 row for each discharge. (Be sure and scroll the table so all cross section 0.0 entries for all cross sections are filled with WSP-S. This sets all initial conditions to use the WSL from STGQ and applies WSP to all cross sections at all discharges.

We have the measured water surface elevations for the three calibration discharges. Will they be different than those predicted by STGQ? To ensure the best precision in calibrating WSP, it is wise to use the known values as the initial conditions. For the three calibration discharges, select **..WSP\User supplies initial WSL** and click the cross section 0.0 entry for each discharge and enter the starting WSL from the data. You have already entered this data as part of the calibration data sets, but to allow for improved estimates of the starting WSL, you must enter it here also.

In the **\Models\WSL\WSP Options** tab, there is a table for entering roughness modifiers (RMODs) for each discharge. The RMODs are used by WSP to adjust the Manning's n values derived in the initial calibration of the longitudinal water surface profiles to account for changes in roughness as a function of discharge. The default value for the RMODs is „1', so initially there is no variation in Manning's n with discharge. These values are modified by the user as needed to obtain a reasonable fit between observed and simulated water surface profiles.

For this exercise, we will use the high discharge as our reference discharge. This is generally a good practice when using WSP as calibration residual errors tend to compress (get smaller) as one simulates downward using backwater type models. As trial values, set the roughness modifiers for 139 cfs and 75.2 cfs to 1.1 and 1.2, respectively. These are strictly trial values so you can start by leaving them at 1.0 if you wish.

Step 2. Run the WSP Program and Determine the Initial Water Surface Elevation Predictions

Click the **Run** button now to run the combined STGQ (at cross section 0.0) and WSP (at all cross sections) model. A message window will indicate when the WSL simulation is completed. Click **OK** to clear this window.

Select the **\Models\WSL\Results** tab or **\Reports** and click on the longitudinal plot option. Select **Observed** and **Simulated WSL** followed by **Refresh**. Zoom on the three calibration discharges by holding down the **Shift** key, moving the mouse to the lower left corner of the region you wish to zoom, holding the **left** mouse button and dragging to the upper right corner of the zoom area. Then release the mouse button and the plot will zoom to that area. Note that **\Models\WSL\Results** contains a table of water surface elevation information for all cross sections and all discharges. In this case, it has seven entries in each row corresponding to the seven discharges we have directed the model to simulate. Note, for example, that the predicted water surface elevation associated with the 250 cfs calibration flow at cross section 201 is 92.936.

How do the simulated values compare with the observed values? Note from the plot that at all three calibration discharges the simulated water surface profile falls considerably below the observed profile. An adjustment to Manning's n is needed. The table in the **\Models\WSL\Results** tab can display the observed, simulated, and difference in water surface elevation at the calibration flows by clicking the **Cal Comparison** radio button. This is useful to display numerical values for the differences seen in the plot.

Step 3. Calibrate WSP for the Longitudinal Water Surface Profile at 250 cfs

For the calibration process it is useful to prepare a table such as Table L5-1 to record successive iterations of the Manning's n adjustment process. The first estimate of the water surface elevation at cross section 60 at 250 cfs recorded in Table L5-1 shows that the predicted WSL is low by 0.185 feet. The calibration strategy will be first to change the Manning's n values at all cross sections simultaneously to get the predicted water surface elevation at all cross sections for our chosen discharge of 250 cfs to fit through the observed values for all cross sections in a reasonable manner. Generally, we would like the simulated values to fit the observed values as closely as possible. We expect some values to be high and some to be low at this stage. Go back to **\Models\WSL\WSP Options** and raise the Manning's n to a new, higher value for all cross sections (.045 is suggested). Remember, raising n increases roughness will thus raise the simulated water surface profile.

Return to **\Models\WSL\WSP Options** and make sure the roughness modifier for a discharge of 250 cfs has a value of 1.0. Then click the **Run** button to run the model. Repeat this process of setting Manning's n , running the model, and viewing results until you have achieved a satisfactory fit between the simulated and observed water surface profile for the 250 cfs discharge.

Figure L5-1 shows the plot resulting from raising Manning's n to 0.45 at all cross sections. Display this plot by clicking the Longitudinal button in the **..\WSL\Results** tab.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

PREFACE

A Brief History of PHABSIM

Use of this Document

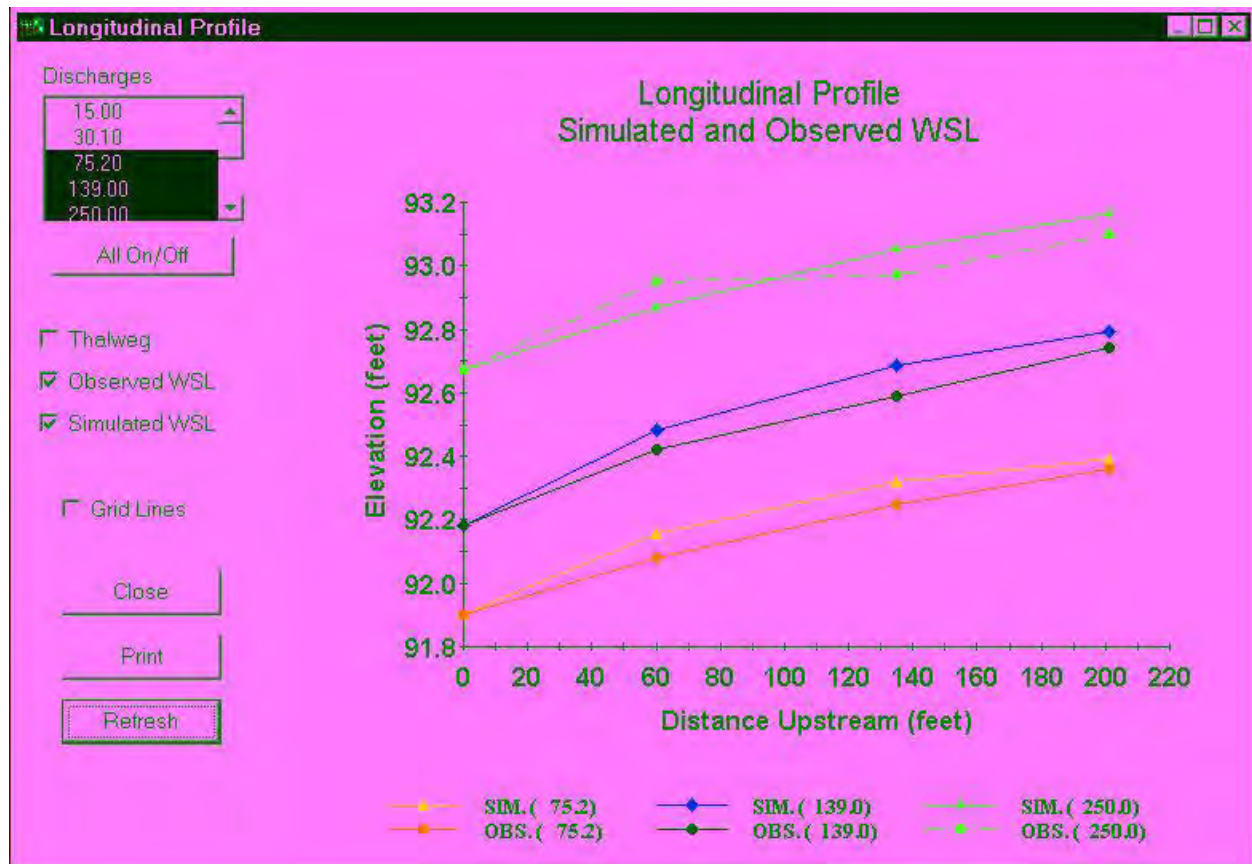
i

ii

Figure L5-1. Water surface profiles

resulting from Manning's $n = 0.045$.

LABORATORY 5 – WATER SURFACE MODELING USING THE WSP MODEL



Increasing the Manning's n from 0.030 to 0.045 raised the water surface profile at all cross sections. Note that the elevation for 250 cfs at cross section 60 changed from 92.765 feet to 92.871 feet. Is this close enough? What about the 250 cfs WSL at the other transects? In this case they are higher than the observed values by 0.081 ft. for transect 135 and 0.066 ft. for transect 201. This would appear to satisfy the criteria of using a single n value to get the best fit through the data. However, we have a dilemma. Notice cross section 60 at 250 cfs. This is the only place where there is a pronounced rise in observed WSL above the values being predicted by WSP. Also notice that, at the other calibration flows, the predicted water surface profile lies above that of the calibration data. Examination of the cross section shapes, the thalweg profile, or relative transect location does not reveal a clear reason for the high observed value at cross section 60. The channel index codes in this study are based on bed material size. There are a few CI values of 7, but the predominant value is 6. The predominant value at cross section 0 is also 6. So, while the bed at cross section 60 may be slightly rougher than at cross section 0, there is no compelling reason to increase roughness above that at cross section 0.

In this particular situation, we may suspect an error in measurement at the high discharge. Following this assumption, we adjust the n values such that the simulated 250 cfs water surface profile closely matches the observed values at the upstream two transects. To accomplish this, reduce the n values in **Edit\Cross Sections** and re-run WSP until good agreement is reached. As you make those adjustments, record n and WSL in Table L5-1. Agreement will occur near $n = 0.041$ at all cross sections.

With global $n = 0.041$, the WSL is 0.109 ft. low at cross section 60, 0.032 ft. high at 135, and 0.005 ft. low at 201. The 0.109 ft. difference seems large. What kind of error may have occurred when the measurements were made? One possible scenario is that the water surface was recorded 0.1 ft. higher than reality. Let us use that assumption and determine which further local adjustments to n should be made to reach a WSL of 92.85 ft. instead of 92.95 ft.

Local adjustments to n are best made in pairs stepping upstream. The Manning's n at the first cross section is changed concurrently with the value at cross section 60.0 since the predicted water surface at cross section 60 is dependent on the initial roughness at the down stream cross section as well as at cross section 60. Changing both Manning's n values also reduces the chance of obtaining unrealistic Manning's n values at upstream cross sections during the calibration process. To reach 92.85, we must raise n at the first two cross sections. Try a value of 0.042.

Go to **\Models\WSL\WSP Options** and enter 0.042 for the first two transects. Then set the roughness modifiers to 1.0 for 250 cfs, 1.1 for 139 cfs, and 1.2 for 75.2 cfs, if you have not already done so, and click **Run**. Look at the table and longitudinal plot in **..\Results**. Note that while the elevation for 250 cfs at cross section 60 has now reached 92.848, the elevations upstream have increased. To get those values back down to within 0.02 ft. of the observed values will require low n values for cross sections 60 and

135. It is possible to set the n value at cross section 0.0 high enough that even a low n value at cross section 60 will produce an elevation of 92.85. However, there is no evidence in this stream that radical changes in n are justified. Thus, the global value of 0.041 appears to be a reasonable best fit value that causes the simulated water surface profile at the selected discharge (250 cfs) to "bracket" the observed values.

Set the n values back to 0.041 for all cross sections and re-run. Now look at the water surface profile (longitudinal) plot. Note that the observed water surface profiles for the three calibration flows appear to arch up in the center and become flatter at cross section 201. This suggests that there is a legitimate increase in roughness between cross sections 135 and 201. Try modifying the n values for those cross sections to obtain a better overall fit for the 250 cfs water surface profile. Be sure to record both the Manning's n values and associated predictions of the water surface elevations in Table L5-1. An approximate rule of thumb is that no more than a 5% – 15% change in n values should occur between transects in an alluvial stream unless there is a topographic or geologic phenomenon to consider. For example, if large car-sized boulders densely filled a short section of stream, large changes in n would be anticipated. That does not appear to be the situation here.

It is important to avoid varying n values merely for the purpose of obtaining an exact fit of the simulated to observed water surface profile. When n values vary substantially between transects, the reliability of extrapolating to higher or lower discharges may be affected. Generally, n represents the combined roughness of the bed particle size and bed form (dunes, for example) that resists the flow of water. Additional losses, such as expansion or contraction losses, are handled to varying degrees within the WSP model. In some circumstances, adjustments to n may be used to ensure such losses are fully represented.

Step 4. Calibration of Roughness Modifiers for Remaining Calibration Data

Now that Manning's n values have been selected to approximately reproduce the water surface profile at the high (250 cfs) calibration flow, the next calibration step involves using a trial-and-error procedure to select RMODs at the remaining calibration flows which most closely reproduce the longitudinal water surface profiles at those discharges. Since WSP treats each simulated discharge independently, calibration of the RMOD for the remaining two calibration flows can occur at the same time. The RMODs represent constants that change the magnitude of the Manning's n values at each cross section while simulating discharges. The RMOD for the calibration flow must therefore be 1.0 and the RMODs at other flows will be either higher or lower than 1.0 depending on whether these discharges are higher or lower than the initial calibration flow. Why?

Recall from Chapter 2 in the manual that roughness or resistance to flow decreases with increasing discharge. Conversely, the roughness should increase as flows are reduced. Since the high calibration flow (i.e., 250 cfs) was used for the initial calibration of the WSP model, the calibrated Manning's n values alone will be too low to correctly predict the water surface elevations at the 139 cfs and 75.2 cfs calibration flows. Therefore, the RMODs at these remaining two calibration flows will need to be greater than 1.0. Think this through and reread Chapter 3 if it is still unclear why. This is why we assigned arbitrary RMODs of 1.1 and 1.2 to the 139 cfs and 75.2 cfs discharges earlier.

Select **\Models\WSL\WSP Options** to display the RMOD table. Set the RMOD values for 139 cfs and 75.2 cfs to 1.1 and 1.2, respectively if they are not already so set. Then select **..\Results** and display the longitudinal plot. Select both **Observed** and **Simulated** water surface elevations and **Refresh** to display them. It is convenient to drag the plot to the lower right of the screen so you can view both the PHABSIM window and plot window simultaneously. In the plot window, magnify (zoom) the area of water surface profiles for the calibration discharges. Now click the **Run** button to run the models. Click **OK** when the program has finished and click the **Refresh** button in the plot window. Where do the simulated water surface profiles for 75.2 and 139 cfs lie in relation to the observed profiles? Are they high or low? Return to the WSP Options tab.

Figure L5-2 shows the predicted versus observed longitudinal water surface profiles at the three calibration flows based on our existing RMODs.

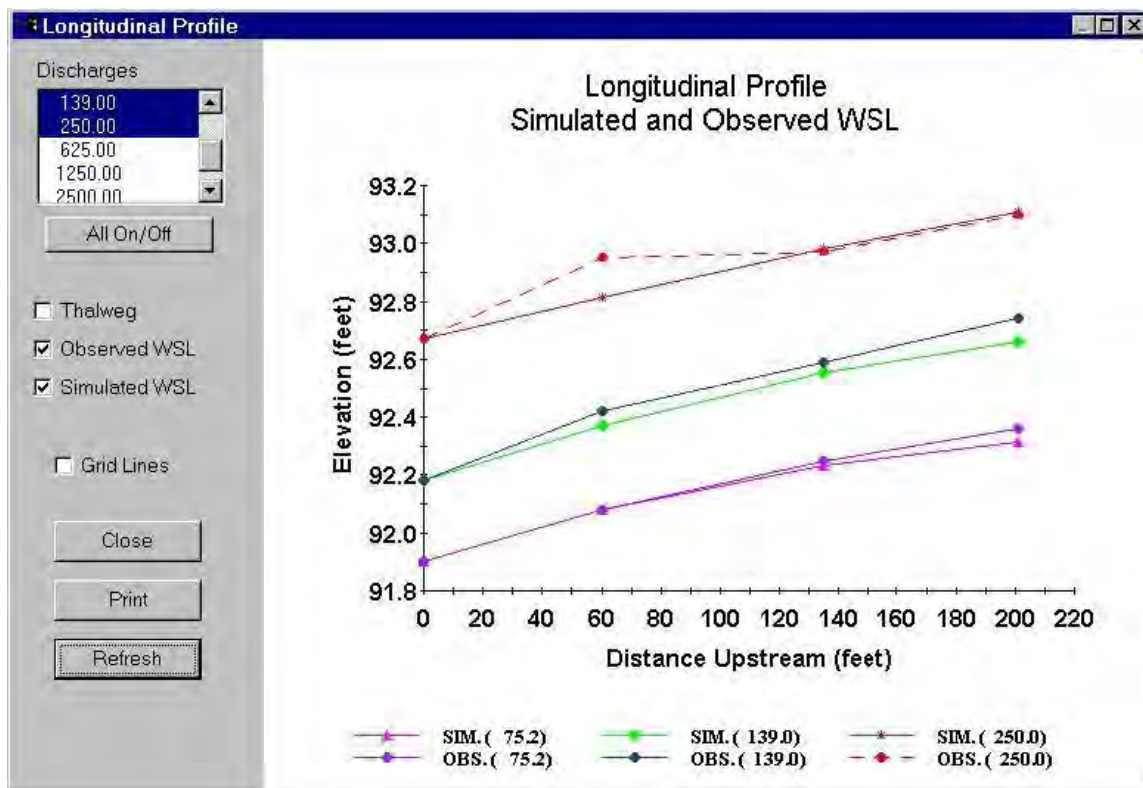


Figure L5-2. Water surface profiles with RMODs of 1.0, 1.1, and 1.2.

This figure illustrates several key factors in the calibration of WSP using RMODs. It should be apparent that the predicted longitudinal profiles for the calibration discharges at 139 cfs and 75.2 cfs 'mimic' the pattern of the water surface profile at the initial calibration flow of 250 cfs. This should be expected since the only effect that the roughness modifiers have in the simulation is to change the magnitude of the Manning's n values and therefore, the relative differences between the individual cross section Manning's n values are retained at the other simulated discharges.

In Figure L5-2 (or by viewing **\Models\WSL\Results\longitudinal**) you can see that the simulated water surface profiles for 139 and 75.2 cfs are generally lower than the observed profiles for those discharges. Do not close the graph window, merely click on the PHABSIM window to move back to it. Remembering that increased roughness will raise a backwater curve, enter new values for the roughness modifiers for 139 and 75.2 cfs in the **\Models\WSL\WSP Options** RMOD table. Click **Run** to re-run the models, click **OK** when the simulation is done and click the **Refresh** button to see the results in the longitudinal profile graph. Continue changing the RMOD values until you achieve the best overall fit at the discharges of 139 and 75.2 cfs. You may record your iterations of this process in Table L5-2.

It should also be noted that if either the 75.2 cfs or 139 cfs flow was selected as the initial calibration discharge, a close agreement between predicted and observed water surface elevations at the other flows would be achieved with the right RMOD. This would be expected given the similarity in the shape of the longitudinal water surface profiles at both of these discharges. However, neither of these lower calibration flows would be expected to achieve close agreement at all cross sections at the high calibration flow given the difference in the observed longitudinal profile at 250 cfs. This should reinforce the concept that

you should carefully consider which initial calibration flow to select, or that you should use multiple calibration flows to see which is best. This determination should be made in light of both model performance and flow ranges of interest in the study.

Staying within the 5%–15% guideline described earlier, try making final small changes to the n values for all cross sections and to the RMODs to best fit all three water surface profiles from cross section 0 to cross section 201. Observe the **diff** column in the **Cal Comparison** table and try to find a set of n values and RMODs that result in not more than a 0.02 ft. difference at all cross sections and discharges. This final step ensures that all observed water surface profile data has been used to achieve the final calibration of WSP over all calibration discharges and over all cross sections. Table L5-3 gives one possible final calibration of n values and RMODs. Other combinations of n and RMOD may give a similar range of WSL calibration errors.

Windows		DOS	Difference	% difference	Table L5-2. WSP RMOD calibration table.
Cell bed elevation	91.65	91.65	0	0.00	
Water surface elevation	92.456	92.47	0.014	0.02	
Depth	0.806	0.82	0.014	1.71	
Depth Suitability Index	0.0708	0.096	0.025	26.25	
Combined Suitability Index	0.0644	0.087	0.023	26.25	
Weighted Usable Area	8.698	11.79	3.096	26.25	
Acknowledgements				i	LABORATORY
PREFACE				ii	5 – WATER
A Brief History of PHABSIM					SURFACE
Use of this Document					MODELING
Changes Between PHABSIM Version 2 and PHABSIM for Windows					USING THE
Conventions Used in this Document					WSP MODEL
Chapter 1, Introduction to the Physical Habitat Simulation System				1	
Objectives					
Associated Laboratory Exercises					
An Overview of IFIM					
The Purpose of PHABSIM					
The Structure of PHABSIM					
Application of PHABSIM					
Scoping					
Selection of Target Species and Suitability Curves					
Selection of Target Species					
Types of Suitability Curves					
Transferability of Suitability Curves					

Table L5-3. A possible WSP calibration.

	Cross section	n value	Discharge	RMOD	
		0.0	0.038	75.2	1.28
		60.0	0.038	139	1.23
135.0	0.043	250	1.00		
201.0	0.043				

Laboratories 3 and 4 demonstrated that neither the stage-discharge or MANSQ models were able to simulate rational (water flowing downhill) profiles at the high discharge range. Let us assume that the current WSP model calibration results are the best that can be achieved and move to the next step in the calibration process.

Step 5. Estimate the Roughness Modifiers for all Desired Simulation Discharges

Assuming that our final calibration effort for RMODs listed in Table L5-2 represents the best compromise in matching the predicted and observed water surface profiles at the medium and low calibration discharges, the next step will involve trial-and-error approximation of a linear log-log relation between n and discharge or development of a regression between the $\log_{10}$ of the discharges and $\log_{10}$ of the RMOD values. The resulting regression equation or approximated relation will then be used to estimate the roughness modifiers for all remaining discharges to be simulated in WSP (i.e., 15.0, 30.1, 625.0, and 1250.0). The log regression is easily accomplished with a spreadsheet program.

Figure L5-3 shows the log-log linear regression results for the relationship between discharge and roughness modifiers obtained using a spreadsheet program. The equation is:

$$\text{Log}_{10}\text{RMOD} = -0.2045 * \log_{10}\text{Discharge} + 0.502 \quad (5-1)$$

This regression equation was used to generate the estimated roughness modifiers listed in Table L5-4 for the remaining simulation flows to be used in the laboratory. Note that the $\log_{10}$ of the discharge must be used in the equation and that the result is the Log_{10} of the roughness modifier. Therefore, the correct RMOD estimate is derived by exponentiating the result from the regression equation as the „x’ in 10^x .

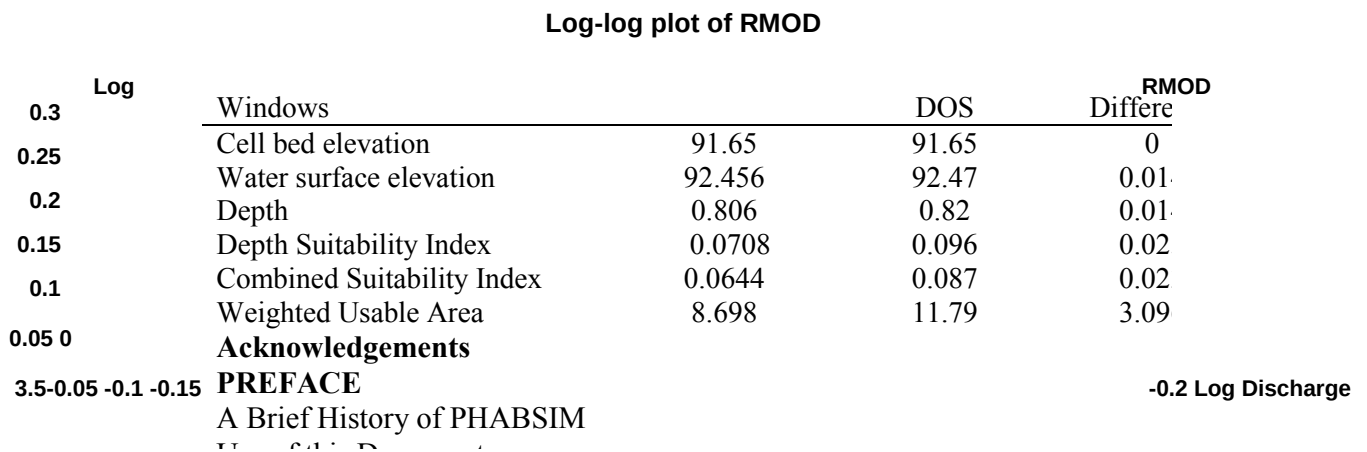


Figure L5-3. Log-log plot of RMOD and discharge.

Table L5-4. Estimated RMOD values at simulation discharges.

Simulation discharge Estimated RMOD

15.0	1.83
30.1	1.58
625.0	.852
1,250.0	.739

Enter these values in the RMOD table in the **WSP Options** tab and click the **Run** button. We now have a water surface profile for each discharge based on the WSP model. The resulting profiles can be viewed using **..\Results\longitudinal**. If you have not already done so, include the remaining target discharges in the simulation by moving to **..\Output Options** , placing a check in all check boxes, and re-running the simulation.

The log-log linear RMOD versus discharge relationship can be visually approximated by trial-and-error by plotting that relationship in PHABSIM for Windows. In the WSP Options tab, click the **Roughness Modifier Graph** button and the **log-log** radio button. Prior to setting RMOD values for the simulation discharges, the graph will look something like Figure L5-4.

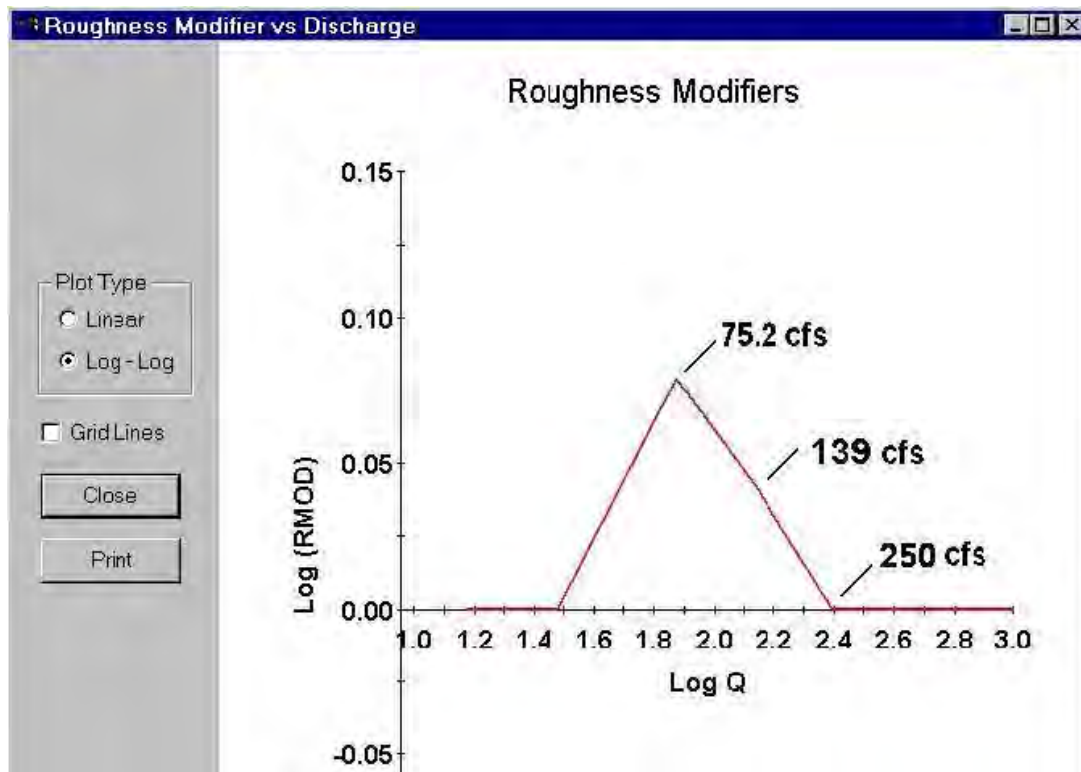


Figure L5-4. Roughness modifier graph.

This plot shows the initial RMODS of 1.0 ($\log_{10}$ of 1 is 0.0) for all simulation discharges and $\log_{10}$ of 1.2, 1.1, and 1.0 for 75.2 cfs, 139 cfs, and 250 cfs respectively. By displaying this plot and the RMOD table in the **..WSP Options** tab simultaneously, the user can quickly build a linear RMOD vs. discharge relationship visually. While not as precise as the regression approach, this is often an adequate approximation for estimating RMOD values.

Step 6. Evaluate the Hydraulic Simulations

In order to check the effectiveness of the hydraulic simulations, we examine the longitudinal profile and calibration error of the water surface elevations for all our simulated data. In particular, the performance of WSP at the high-simulated discharges is of interest, since neither STGQ nor MANSQ were able to produce rational results above our high calibration flow of 250 cfs.

Zoom in on the water surface profiles for 625 cfs and 1250 cfs in **..Results\Longitudinal**. Compared to the STGQ and MANSQ results these profiles show water running downhill at the high discharges. The WSP model produces rational results for the high-simulated flows. This would suggest that the WSP model could be used for simulations above the highest calibration flow (i.e., above 250 cfs).

Now zoom in on the water surface profiles for 15 cfs and 30 cfs. Do these results also look rational? It does appear that a weak pool is produced by backwater from cross sections 0.0 and 60. Neither of those sections shows clear evidence of being a strong control. More likely, control is the result of the overall resistance of the channel between those two sections. This condition is often referred to as channel control and helps explain the observed and simulated water surface profiles seen here.

You may compare the water surface profiles developed using WSP and STGQ by starting another copy of PHABSIM and loading the lab03 SAMPLE data set. Longitudinal plots for both data sets can be displayed on the screen at once by sizing windows appropriately. Do not try to load two copies of the same project.

Based on these results, the WSP simulated water surface elevations will be used for the subsequent steps in the laboratory exercises.

A final note: We ignored the water surface elevation at cross section 60 for 250 cfs and assumed it was a measurement error. What if it was not a measurement error? What would need to be done differently in this WSP calibration to achieve the “best” simulation? Specifically, could we stay within the 5%-15% change in n guideline? Could the maximum water surface simulation error be held to $\nabla 0.02$ ft.? How would the RMODs change?

To explore these questions you can make a copy of the project at the present stage using **\File \Save As** and re-calibrate assuming that the cross section 60 value is correct.

Laboratory 6. Velocity Modeling – VELSIM Objectives

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i
..

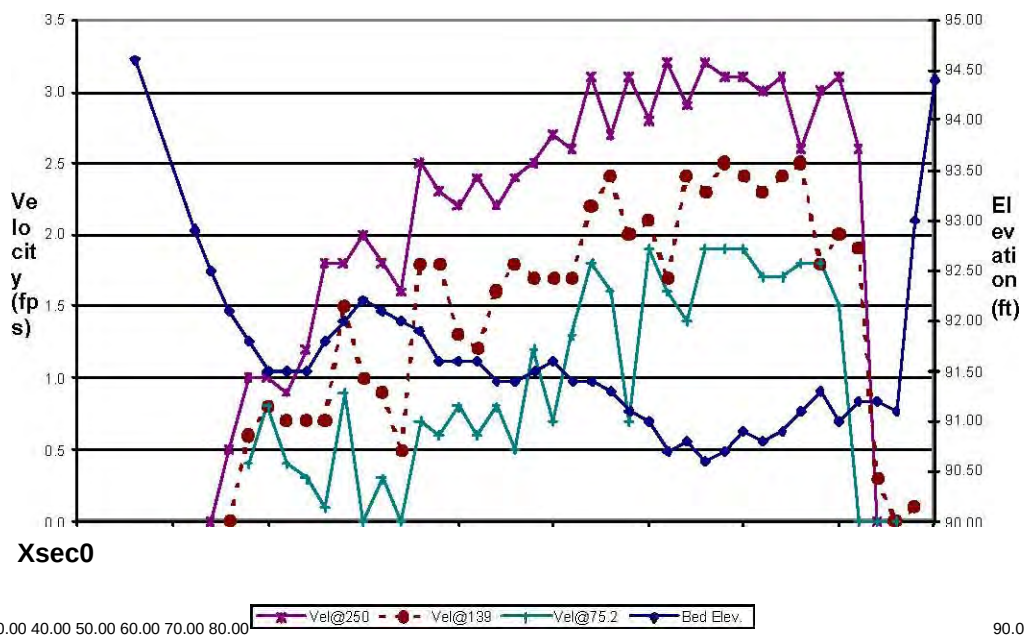
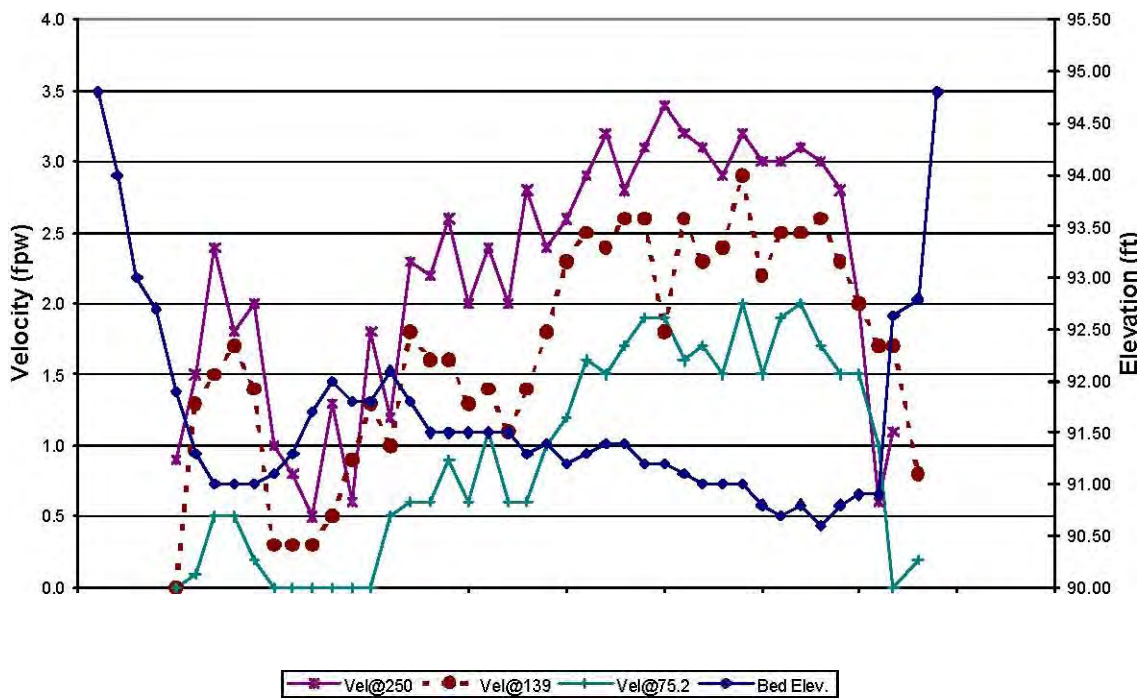
The objectives of this laboratory are to explore various methods for velocity modeling within PHABSIM using the VELSIM program and to introduce the basic techniques for evaluation of the effectiveness of

In this laboratory, different empirical approaches to simulating velocities are examined. Recall from Chapter 2 of the manual, that VELSIM can use specific velocity calibration sets for specific ranges of discharges, and a conveyance area-based velocity distribution can be developed when no calibration velocities are available. The 'best' approach can only be determined by evaluating a combination of available data, model performance, and objectives of the particular study.

This laboratory explores several different velocity set combinations and simulation control options within VELSIM to help the user understand the effects and consequences of selecting a particular velocity calibration data set and modeling option(s) within VELSIM. The laboratory is also intended to demonstrate the implications of selecting a particular water surface elevation model and subsequent effects during the simulation of velocities in VELSIM. The overall objective of velocity calibration and simulation is to pick the best combination of calibration velocity(s) and simulation options to represent the velocity profiles at each cross section over the range of simulated flows. The steps in this lab provide a good sequence for velocity simulation.

Step 1. Evaluate Observed Velocity Profiles

Prior to beginning the modeling efforts, examine the observed velocity profiles at each cross section for all three calibration flows provided in Figures L6-1 through L6-4. The velocity profiles between different cross section geometries are highly variable as would be expected. Also note, however, that the velocity patterns at specific cross sections are 'generally' similar at all three calibration flows, but differences in the location of high versus low velocities and changes in the transverse patterns of velocities between the different calibration flows are also evident.



Distance from Head Pin

Figure L6-1. Observed velocity distribution for cross section 0.0.

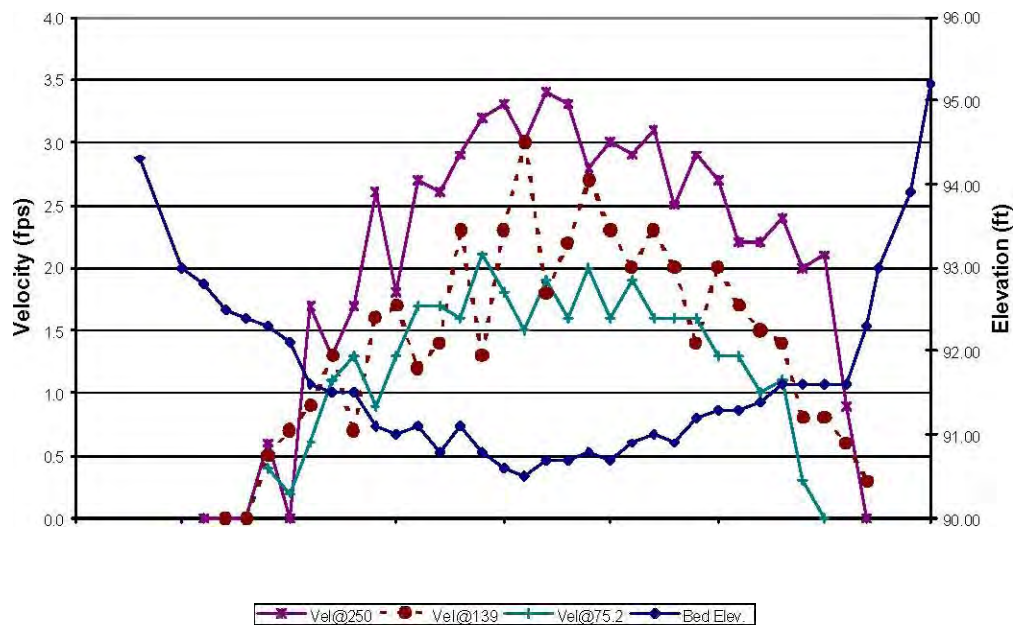
Xsec6

0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00 90.00

Distance from Head Pin

Figure L6-2. Observed velocity distribution for cross section 60.0.

LABORATORY 6 –VELOCITY MODELING – VELSIM



Xsec135

0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00
Distance from Head Pin

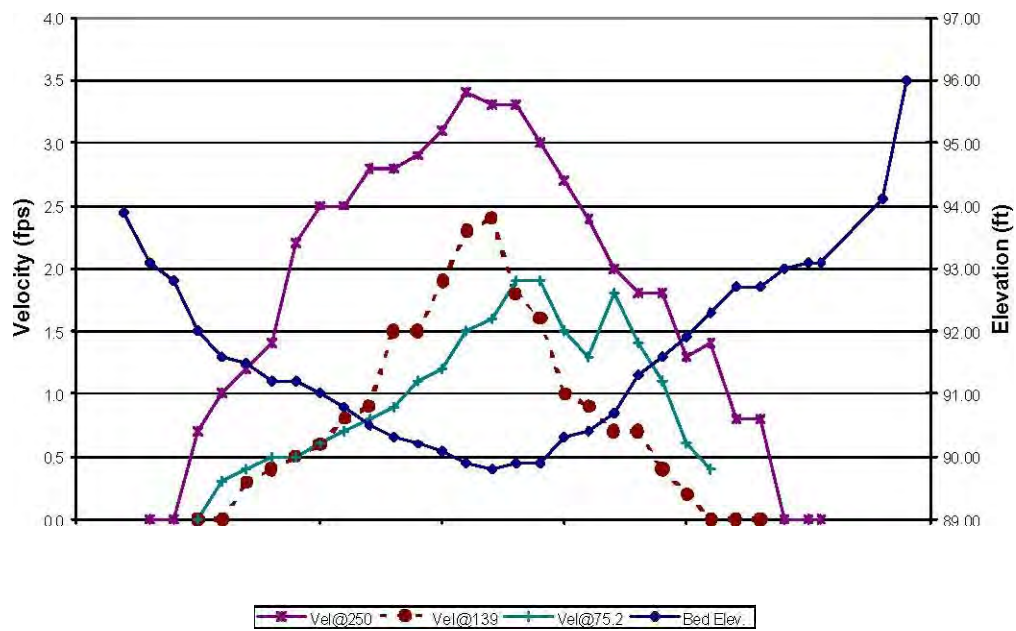
Figure L6-3. Observed velocity distribution for cross section 135.0.

Xsec201

0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00
Distance from Head Pin

Figure L6-4. Observed velocity distribution for cross section 201.0.

LABORATORY 6 –VELOCITY MODELING – VELSIM



Step 2. Assign Velocity Calibration Sets for Simulation of Velocities Go to \Models\Velocity Simulation\Velocity Calibration Set Assignments and assign velocity sets as shown in Table L6-1.

Table L6-1. Initial velocity set assignments.

Transect Discharges

15	30	75.2	139	250	625	1,250	01	1111	11
601	1111	11	1351	1111	11	2011	1111	11	

Assigning velocity set 1 to all cross sections and discharges tells the program to use the low calibration discharge velocity distribution as the template for simulating discharges across the entire flow range of the study. Later we will reset some or all of these values and compare the different velocity simulation results to obtain a final set of assigned calibration sets to use for each transect and discharge combination in this table.

We can now simulate velocities for all discharges at all cross sections using the low flow calibration set as the velocity distribution template. Remember that water surface elevations (WSLs) were previously established using the WSP program.

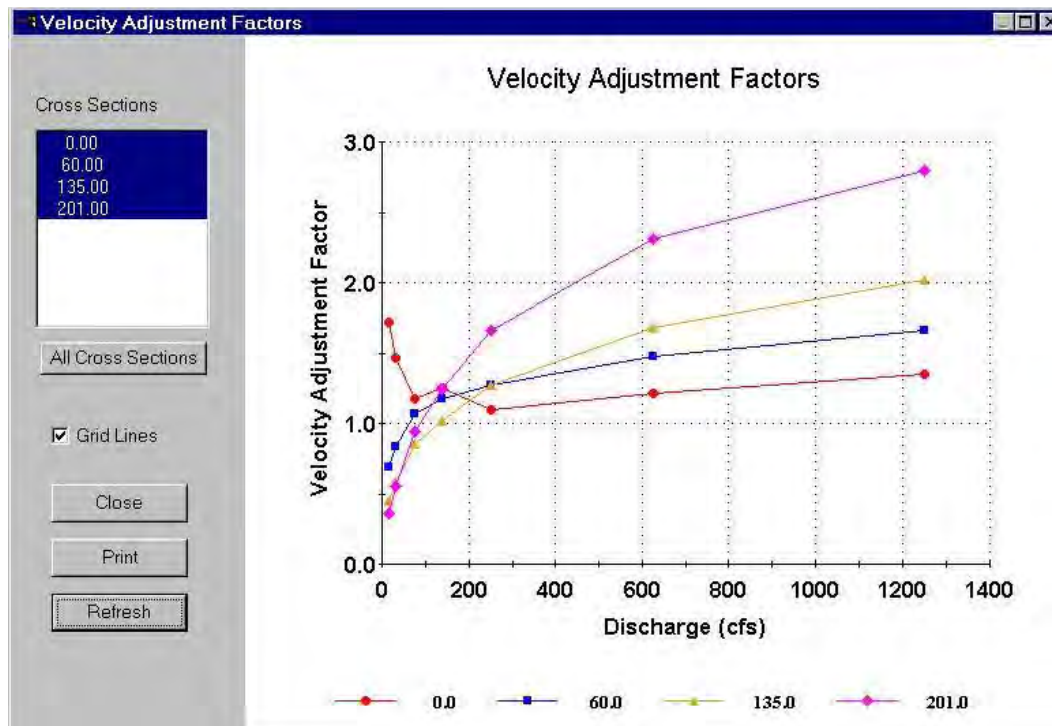
Step 3. Velocity Simulations Based on Different Velocity Calibration Data Sets

Begin by simulating velocities using the low discharge calibration set as the velocity distribution template. To do this, click the **Run** button. When the VELSIM program has completed its execution. A small message box will announce velocity simulation is finished. Click **OK**.

Now click the **Results** tab and the **Cross section** button at its bottom to display cross sectional plots. Click on 75.2 in the discharges table to display results for 75.2 cfs for cross section 0. Click the check boxes such that a check shows in all four boxes for **Observed WSL, Simulated WSL, Observed Velocities, and Simulated Velocities**. Now click the **Refresh** button. The graph should look like Figure L6-10. To view it better, use the Windows maximize button in the upper right corner of the graph window. You can now visually compare the observed and simulated velocities at a discharge of 75.2 cfs for cross section 0 based on using the 75.2 cfs calibration set as the velocity distribution template. Click on cross section 60 in the box at the top left of the window and then the **Refresh** button. The graph changes to display the WSL and velocity data and simulation results for cross section 60 at 75.2 cfs. In the classroom situation, it would take too long for each student to make printed copies of all of the plots of observed and to simulate velocities based on different templates, so the results of using calibration set 1, calibration set 2, and calibration set 3 for all cross sections at all discharges are given in Figures L6-10 through L6-45 at the end of this laboratory.

A cursory examination of these figures shows that the best fit occurs when the simulated discharge is equal to the calibration set discharge. So it seems reasonable to use Cal Set 1 for discharges less than or

equal to 75.2 cfs, Cal Set 2 for 139 cfs, and Cal Set 3 for discharges greater than or equal to 250 cfs. Try assigning calibration sets in that order and run the model again. Figures L6-5 to L6-8 contain the VAF relationships for the



four velocity template runs. These results will be compared in the next section.

Figure L6-5. Velocity adjustment factor for calibration flow of 75.2 cfs.

LABORATORY 6 –VELOCITY MODELING – VELSIM

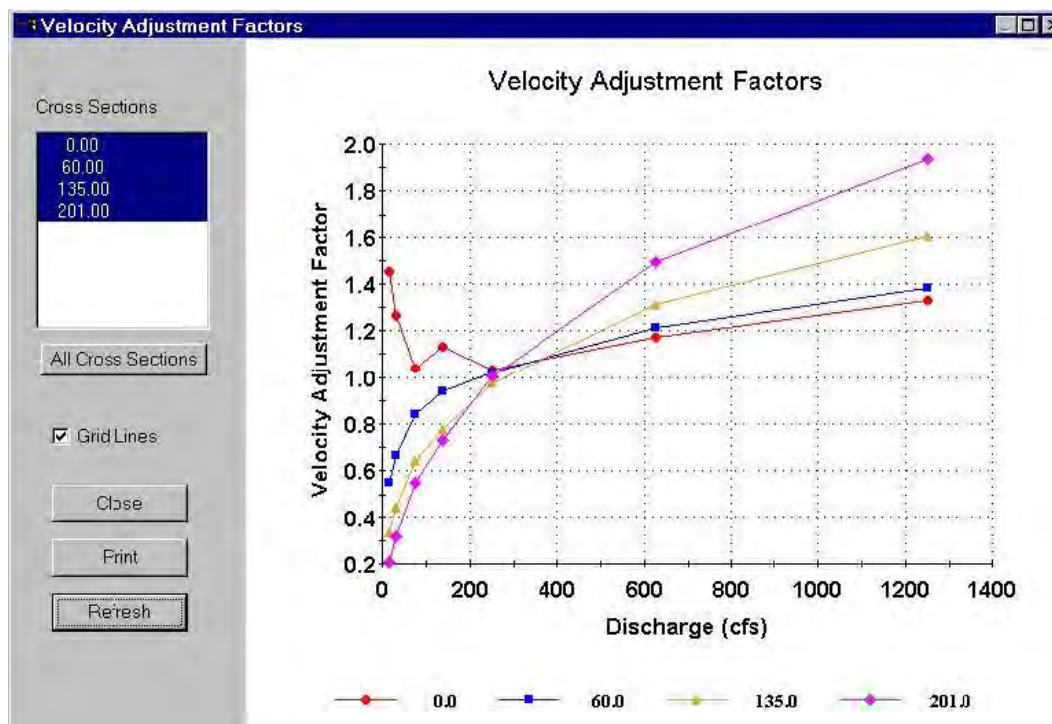
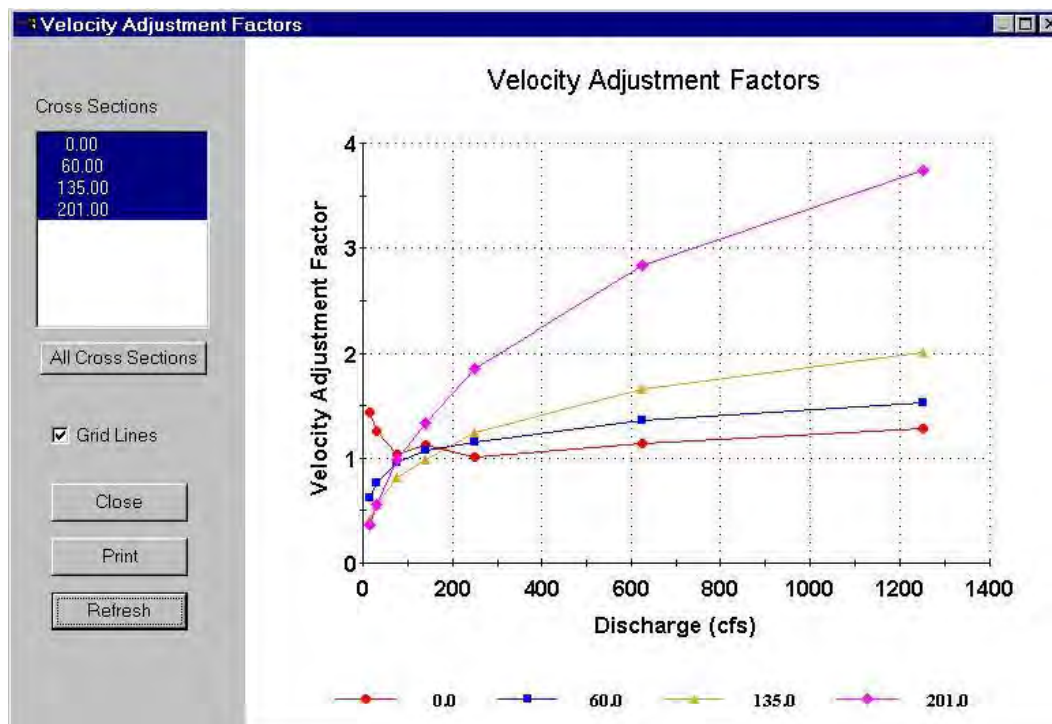


Figure L6-6. Velocity adjustment factor for calibration flow of 139 cfs.

Figure L6-7. Velocity adjustment factor for calibration flow of 250 cfs.

LABORATORY 6 –VELOCITY MODELING – VELSIM

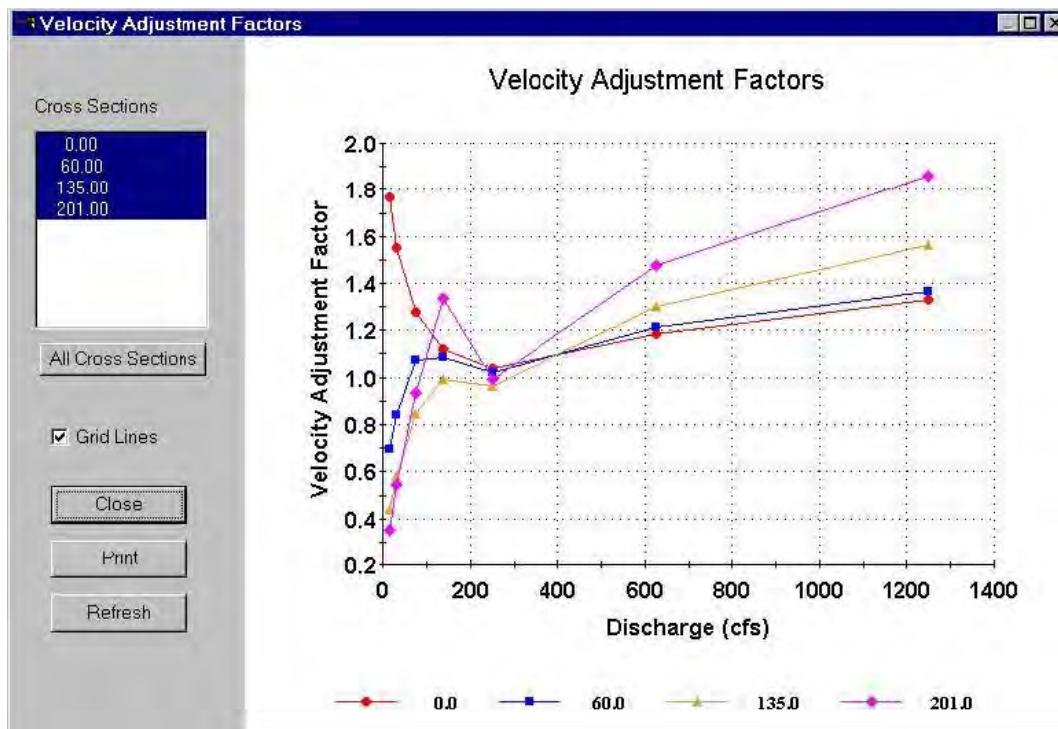


Figure L6-8. Velocity adjustment factor for mixed calibration flow sets.

Step 4. Examine the VAF Relationships and Velocity Profiles

We will first examine the VAF relationships for each of the four simulations. Remember, velocity predictions at a simulated discharge are a function of the Manning's n derived from the calibration velocities at a single calibration flow. Also recall that VELSIM uses the VAF to maintain mass balance between simulated and computed discharges. Since roughness decreases with increasing discharge, VAF's below the calibration flow should generally be less than 1.0 and greater than 1.0 for flows above the velocity calibration flows. The degree to which the VAF departs from 1.0 at the velocity calibration flow is a function of the difference between the calculated discharge and the „best estimate of the discharge’ as well as the difference between predicted and observed water surface elevations (see Chapter 2 in the manual).

In Figure L6-5 (where the 75.2 cfs calibration set was used to simulate all discharges), all the VAF relationships except at cross section 0 follow the expected pattern. The relationship at cross section 0 „suggests’ that roughness is decreasing with as the discharge decreases below 139 cfs, which is counter to expected results. The remaining cross sections appear to behave „normally’.

The VAF relationships for all four simulations are shown in Figures L6-5 to L6-8. We can learn several things by comparing these figures.

First, it should be apparent that the use of a single velocity calibration set results in VAF relationships, which are more 'typical' of expected results for all but cross section 0. Use of a mix of all three velocity sets produces an irregularity between 75.2 and 250 cfs for all but cross section 0. Though the VAF traces appear to have a break in slope at either 75.2 cfs or 139 cfs and drop to the value at 250 cfs, they do

appear to be ascending with increased discharge within each range of simulation, e.g. 0.0 – 75.2 cfs and above 250 cfs. As only one discharge was simulated using the 139 cfs template, we do not know if this will hold true for the 139 cfs calibration set without running additional discharges. What do the other VAF plot suggest?

Note the magnitude of the velocity adjustment factors using the four different approaches. These results show that the choice of a particular velocity calibration data set can impact both the magnitude and functional relationship of the VAF's. As might be expected, since the WSP modeled water surface elevations were used for these simulations, the VAF relationship for the high flow velocity set is „best behaved’ over all ranges of simulated discharges. The results at cross section 0 would suggest that either alternative velocity simulation options in VELSIM should be attempted, that an alternative water elevation modeling approach may be required, that a combination of the two may be warranted, or that the channel conditions warrant further study.

Although an examination of the VAF relationships helps in the general diagnostics of the velocity simulations, an examination of the actual predicted velocities for each vertical for all cross sections at all simulated discharges must be undertaken to critically evaluate the simulation results. Actual velocity predictions should receive more emphasis than „strict’ adherence to an expected pattern of the VAF relationships in evaluation of the effectiveness of the velocity simulations.

A careful examination of the results shown in Figures 10 – 45 should reveal several key points about this particular data set and VELSIM velocity simulations in general. First, the predicted velocities at a given calibration flow using that calibration flow velocity set do not exactly reproduce the observed velocities. The velocities measured at each cross section do not necessarily result in a computed discharge equal to the best estimate of the discharge or calibration discharge. Thus, the predicted velocities are adjusted by the computed VAF to maintain mass balance between the simulated flow and computed flow at the cross section (see Chapter 3 in the manual).

The second thing to note is that at a given calibration flow, using that calibration flow velocity set results in some computational cells at the stream margin that have predicted velocities where none were observed. This is due to the discrepancy in the observed and predicted water surface elevations at each cross section and possible errors in the original data.

It should also be apparent that the velocity pattern at the calibration flow used in the simulation is „replicated’ at all simulation flows. This can result in relatively large discrepancies between observed and simulated velocities when using for example a low velocity calibration set to simulate high flows or vice versa. This can often occur when the velocity profiles change dramatically between discharges due to channel geometry heterogeneity, especially due to unobserved conditions upstream of the transect.

Collection of a single high flow velocity data set for use in modeling should be carefully evaluated based on complexity of the channel geometry at specific cross sections. If significant changes in velocity profiles are expected over different ranges of discharge of interest in a study, additional velocity data sets should be collected.

The results also suggest that simulation of velocities higher than an observed calibration velocity data set can be problematic at some cross sections since VELSIM must „guess’ at a Manning’s n value for computational cells where no observed velocities have been provided at the velocity calibration flow.

The simulation results for cross section 201.0 also demonstrate the influence of water surface modeling on the predictions of velocities with VELSIM. Go to **Results\Graphs\Longitudinal Profile** and zoom in on the region encompassing the three calibration discharges. Note that at cross section 201.0 the WSP

model is slightly under-predicting the water surface elevation at the 139.0 cfs and 75.2 cfs calibration flows. Now view **Results\Graphs\Cross Section** and select cross section 201, discharge 75.2 cfs, observed and simulated WSL and velocities. At 75.2 cfs VELSIM predicts slightly slower water at the cross section but one cell on the left bank shows a simulated velocity of 0.236 fps where the calibration velocity was 0.0. This provides enough conveyance to slightly lower the other velocities. At 139 cfs, however, the simulated velocities are significantly higher than the observed velocities. The simulated water surface elevation is 0.001 ft higher than the observed value, not a significant difference. Yet, the velocities are slightly higher. Why? Noting the calibration data, we find that the local discharge was 249 cfs, but the best estimate discharge is 250 cfs. Thus, a VAF slightly greater than 1.0 was needed to achieve mass balance resulting in a very slight increase in velocities in spite of the slightly higher WSL.

In general, improving the water surface elevation predictions for any cross section at the calibration flows would bring the simulated cross sectional areas closer to the observed values. This would therefore reduce the VAF adjustments and result in a better match between observed and predicted velocities at the lower calibration flows. This can be seen the results at the 250 cfs calibration flow which identically match the calibration velocities over most of the cross section. Try simulating additional discharges that match the local discharges measured at cross sections 60 and 135. Do the simulated velocity results match the observed values better?

The final water surface elevation simulation using WSP allowed a very large difference (0.137 ft.) between the observed and predicted water surface elevation at cross section 60 for the 250 cfs discharge. This was based on the assumption that an error of at least 0.10 ft. had been made in the water surface measurement at that discharge. In spite of the large difference in water surface elevation, the simulated velocities are only slightly lower than the observed velocities. Two cells at the right of the channel, which have significant simulated velocities when the measured velocities were zero, explain the lower velocities. The overall close agreement in simulated and observed velocities further supports the assumption of a water surface elevation measurement error.

No single velocity calibration set is guaranteed to work at all ranges of simulated discharges at all cross sections. The 3-calibration data set approach would appear to represent the best compromise at all cross sections for all flow ranges. Selection of an appropriate velocity set(s) should be carefully considered in light of model performance and study objectives. These results should reinforce the importance of accurate water surface elevation modeling prior to undertaking the velocity modeling in VELSIM. A critical examination of the velocity modeling can also be used to revise water surface modeling approaches (for example, what to do with cross section 60) based on the effectiveness of the velocity predictions at specific ranges of discharge of importance to a particular study.

Step 5. Revise Water Surface Elevations at Discharges below 250 cfs Based on MANSQ

The water surface elevation modeling conducted in Laboratories 3, 4, and 5 indicated that either the VELSIM or MANSQ model matched the observed water surface elevations at the medium and low calibration flows. In this step of the laboratory, the WSL data for each cross section will be updated to use the water surface elevation predictions derived from the MANSQ model for all simulation flows below 250 cfs. Table L6-2 lists the water surface elevations for each cross section that will be used for this part of the laboratory.

Table L6-2.	Windows		DOS	Difference	MANSQ
derived water	Cell bed elevation	91.65	91.65	0	surface
elevations for	Water surface elevation	92.456	92.47	0.014	each cross
section.	Depth	0.806	0.82	0.014	
	Depth Suitability Index	0.0708	0.096	0.025	
	Combined Suitability Index	0.0644	0.087	0.023	
	Weighted Usable Area	8.698	11.79	3.096	

Go to **Acknowledgements**

\Models\WSL\Method and set the starting combination for the WSP backwater at cross section 0.0 for discharges of 75.2 and 139 cfs to WSP-MANSQ and **Run** the selection.

Now go to \Models\Velocity and click **Run** to re-run the velocity simulation using the new elevations derived from using MANSQ as the starting point in the WSP backwater calculation. Compare the VAF relationship in Figure L6-9 with Figure L6-8. Updating the WSLs at the lower discharge ranges (i.e., below 250 cfs) improves the VAF relationship at cross section 0.0 by reducing the variation above a VAF value of 1.0 even though it does not result in transforming the VAF curve into the desired shape.

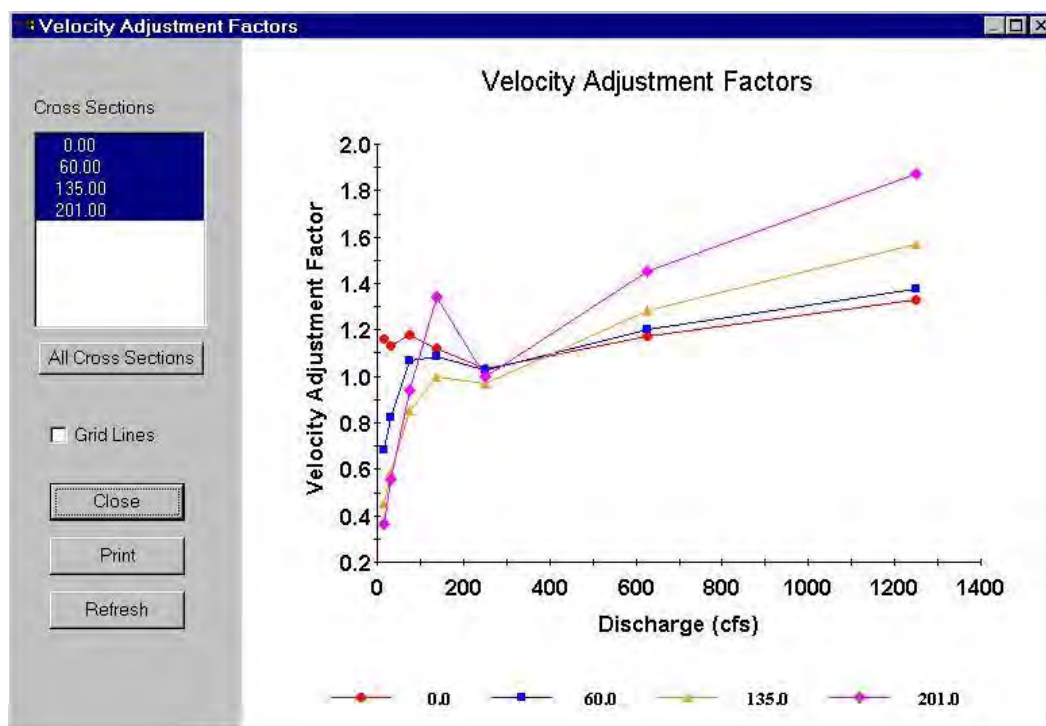


Figure L6-9. Velocity adjustment factors using MANSQ for low flow starting WSLs.

Based on these simulation results, the user would likely conclude that if only one calibration set is to be used, the high velocity calibration data set could be used for all ranges of simulated discharges. Alternatively, the user could also use each velocity calibration data set over a specific range of simulated discharges such as the high velocity calibration set for all flows greater than 250 cfs and for flows down

to a discharge of 139 cfs. The 139 cfs velocity calibration data set could then be used to model flow down to 75.2 cfs and then use the 75.2 cfs velocity calibration data set for all lower simulated discharges. The choice of modeling strategy is a matter of professional judgment based on the quality of the available data. The goal is to produce a simulated velocity distribution that is as near as possible to that which occurs in the stream. A carefully kept set of analysis notes explaining why a particular strategy was selected is strongly advised. PHABSIM for Windows maintains a **History.project name** text file that records the order of model runs. This file can be periodically copied to another file and annotated as a means of tracking the analysis.

Step 6. Use of the NMAX Option in VELSIM to Control Velocity Simulations

One of the ways to control velocity simulations in VELSIM is to restrict the magnitudes of the estimated Manning's n values. This can be accomplished by using the NMAX or NMIN options. Restriction of Manning's n values can often improve velocity simulations in computational cells at the margin of the stream where velocity calibration data does not exist (i.e., verticals in the channel above the highest velocity calibration data set). Since velocity simulations at the stream margins can be controlled, the velocity predictions at all other verticals are also affected due to the interaction of conveyance and the VAF's.

Selection of a limit on Manning's n , whether a maximum or minimum, is a matter of professional judgment. One rational approach is to examine the calculated Manning's n values at computational cells along the margins of each cross section for each calibration flow and select a Manning's n which is an 'average' of these values. Alternative approaches include the estimation of a Manning's n value using handbook values (see Chapter 3 in the manual) based on substrate characteristics. It should be noted that use of an NMAX and/or an NMIN applies to all computational cells at all cross sections at all flows when running VELSIM. Therefore, in those instances where substrate characteristics vary dramatically between cross sections, separate VELSIM data files containing only selected cross sections may be necessary. In this laboratory, the NMAX constraint will be applied to the entire data set over all ranges of simulated discharges.

Go to **\Models\Velocity\Options** and check the box labeled **Limit Manning's n** . Enter an NMAX value of 0.035 and click the **Run** button. Then view the VAF relation by clicking the **ZVAFF** tab and its **Graph** button.

It is apparent the constraint of Manning's n values to a maximum of 0.035 has resulted in a reduction in the magnitudes of the VAF's at all cross sections. This would be expected since lowering the upper limit on estimated Manning's n should result in higher velocity predictions. This in turn should decrease the VAF that is derived from the ratio of simulated discharge over computed discharge. A comparison of predicted Manning's n and velocities at the first 25 computational cells at cross section 135 at 15 cfs clearly illustrates the effect of NMAX on velocity modeling (Table L6-3).

Windows		DOS	Difference	% difference	Table
Cell bed elevation	91.65	91.65	0	0.00	L6-3.
Water surface elevation	92.456	92.47	0.014	0.02	
Depth	0.806	0.82	0.014	1.71	
Depth Suitability Index	0.0708	0.096	0.025	26.25	
Combined Suitability Index	0.0644	0.087	0.023	26.25	
Weighted Usable Area	8.698	11.79	3.096	26.25	

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Selection of Target Species

Types of Suitability Curves

Transferring of Suitability Curves

Comparison of Manning's n and velocity predictions at cross section 135.0 at 15.0 cfs.

The overall pattern of velocities generated by limiting Manning's n needs to be considered before accepting the improved VAF relation as the best velocity simulation outcome that can be obtained for velocity simulation. Using **Models\Velocity\Results\Cross section**, look at the velocity patterns obtained for each cross section at the three calibration discharges. How well do they match? Do you think that limiting Manning's n has improved the overall velocity simulation across all transects over the full range of discharges?

At this point in the analysis, users would need to determine from the context of their particular application which set of velocity simulation options and results is best over what target flow ranges in choosing the appropriate velocity modeling approach. In some applications it may be desirable to use simulation results that minimize the error between measured and observed velocities over the full range of simulations. In other situations, the investigator may choose to use each single velocity calibration set only over a specific range of discharges. This is often the case where velocity patterns vary dramatically across cross section geometries as discussed in Chapter 2 of the manual.

Step 7. Specifying n values for Problem Areas

Look through Figures L6-10 to L6-45 for those cases where simulated discharge is equal to the calibration discharge. Note that some edge conditions are not well simulated due to being dry at the observed discharge. Table L6-4 contains a summary of the diagnostic conditions revealed by those figures. Some data errors can be seen and some velocity simulation problems stand out.

LABORATORY 6 –VELOCITY MODELING – VELSIM

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

An Overview of IFIM

The Purpose of PHABSIM

The Structure of PHABSIM

Application of PHABSIM

Scoping

Selection of Target Species and Suitability Curves

Table L6-4. Summary of data and simulation diagnostic conditions.

In **\Edit\Cross Sections \Coordinate Data** you can set Manning's n values for specific cells on each cross section. After examining how VELSIM handles edges (or other parts of the channel) automatically, you may wish to enter n values for specific cells and rerun the velocity simulation. Roughness values set for specific cells apply at all discharges so you must take care that a good n value for one condition does not perturb the results for other discharges. Try setting n values on the left bank of cross section 201 for 250 cfs, rerun the simulation, and see how velocity values are affected at all flows.

The user is encouraged to try additional velocity simulation options within VELSIM (e.g., placing specific Manning's n values at specific verticals or using the NMIN option). Examine the effects on the velocity simulations in terms of both the VAF relationships and observed versus predicted velocity distributions at each cross section. Remember that water surface simulations for each cross section affect the velocity simulations. In some cases water surface errors can be the main contributing factors for discrepancies between observed and predicted velocities.

LABORATORY 6 –VELOCITY MODELING – VELSIM

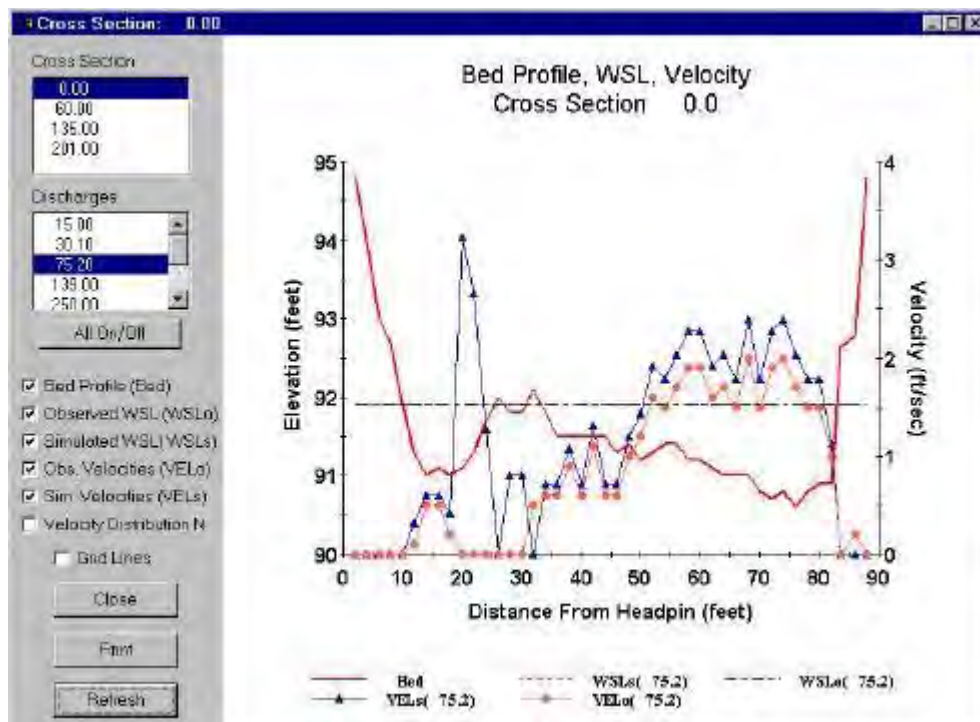


Figure L6-10. Simulated and observed velocity profile for 75.2 cfs at Xsec 0, Cal Set 75.2.

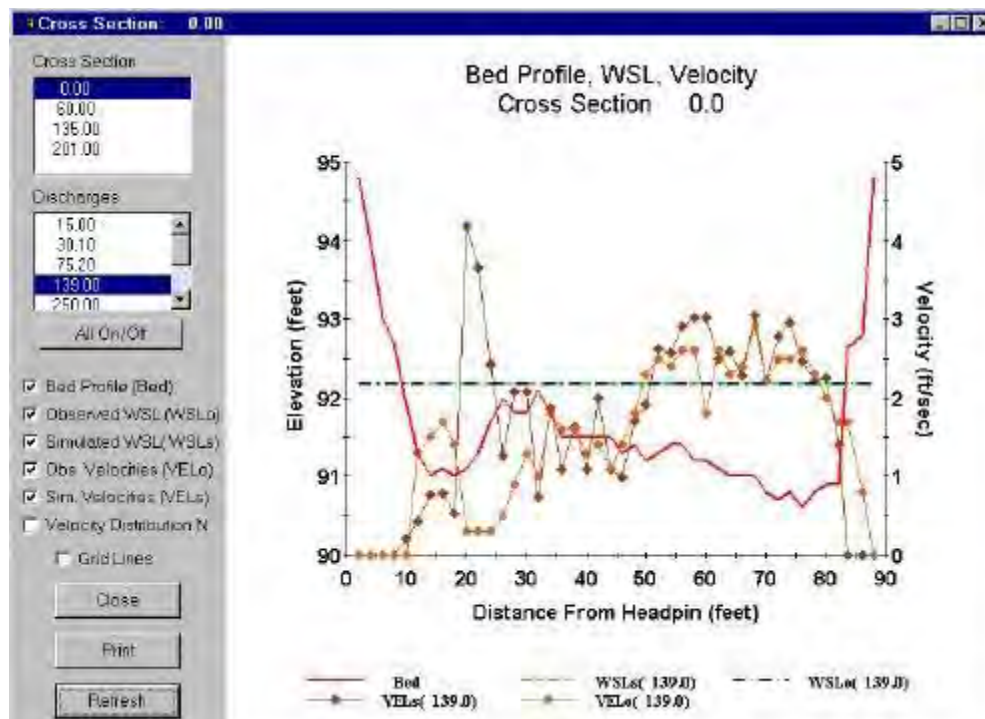


Figure L6-11. Simulated and observed velocity profile for 139 cfs at Xsec 0, Cal Set 75.2.

LABORATORY 6 –VELOCITY MODELING – VELSIM

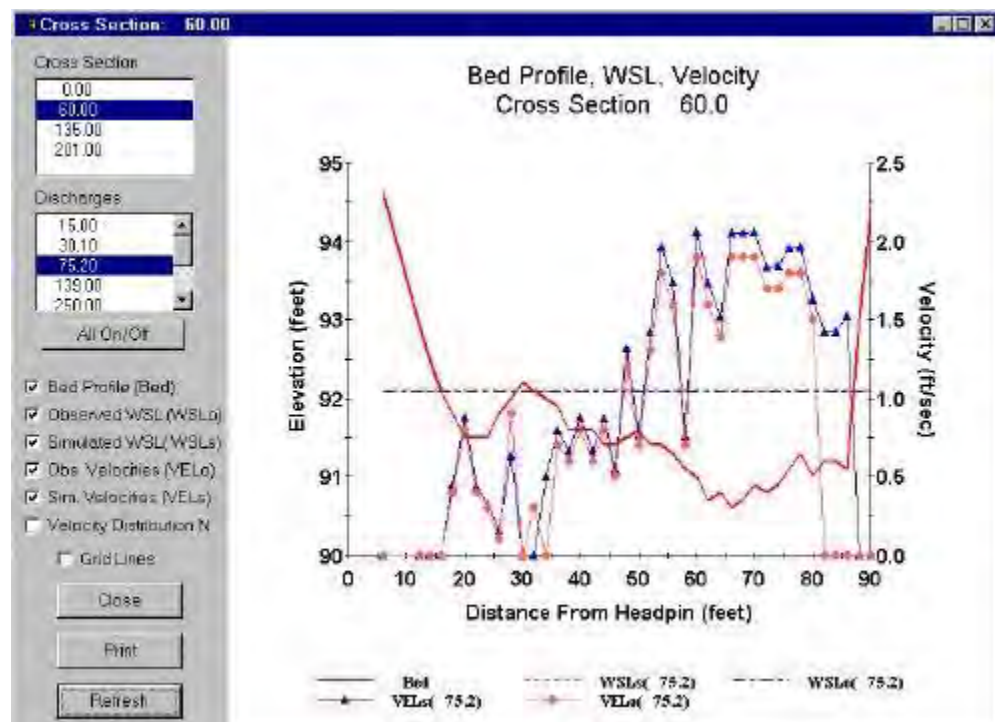
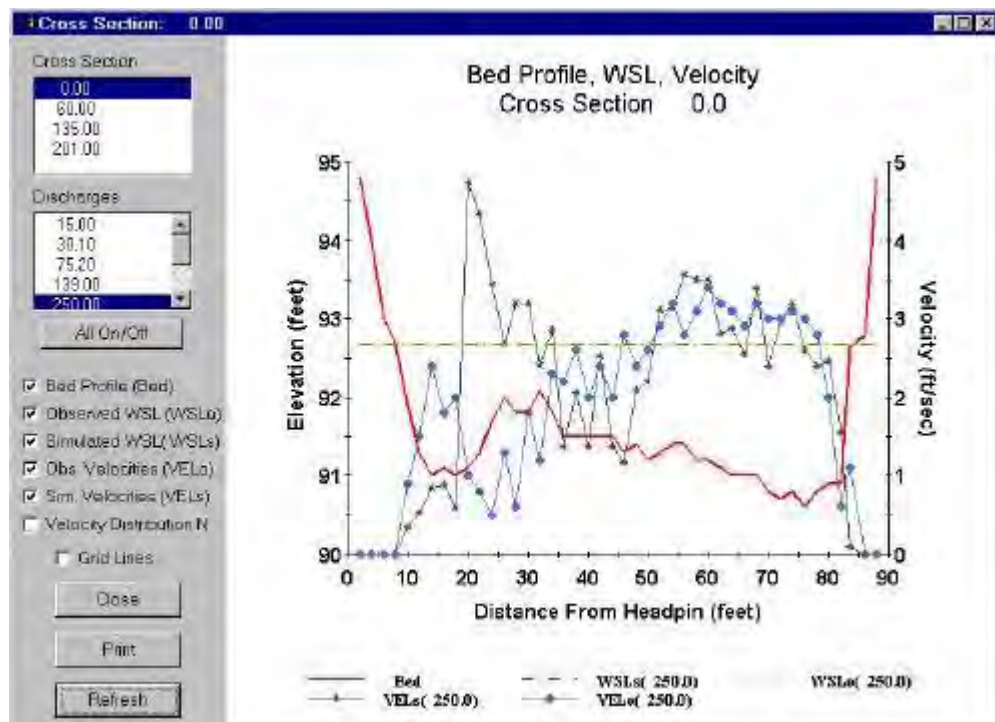


Figure L6-12. Simulated and observed velocity profile for 250 cfs at Xsec 0, Cal Set 75.2.

Figure L6-13. Simulated and observed velocity profile for 75.2 cfs at Xsec 60, Cal Set 75.2.

LABORATORY 6 –VELOCITY MODELING – VELSIM

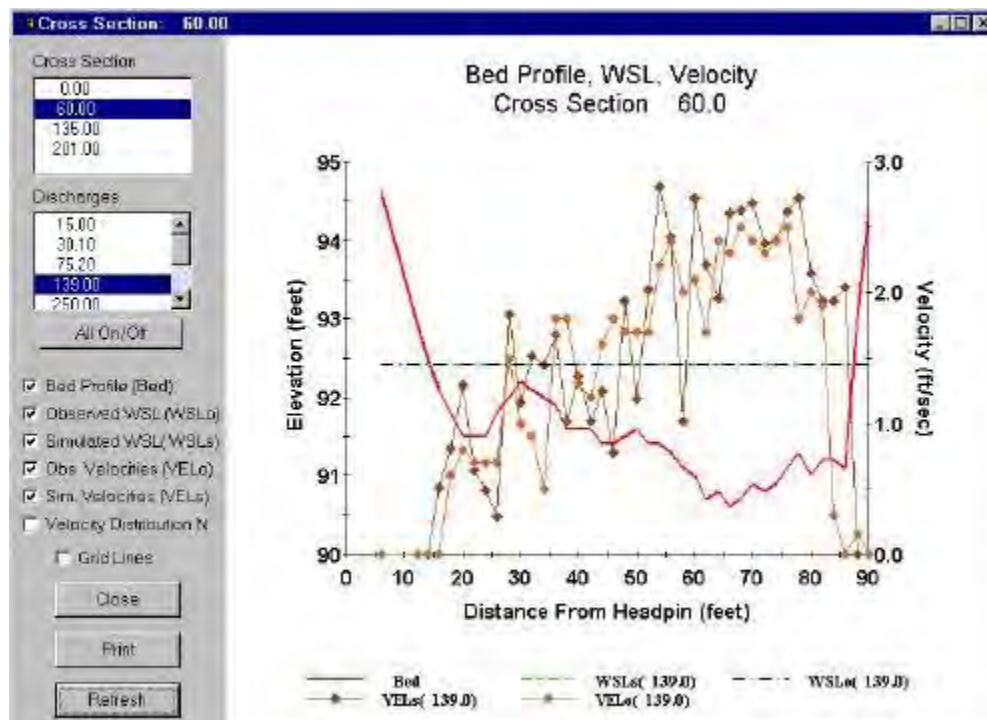


Figure L6-14. Simulated and observed velocity profile for 139 cfs at Xsec 60, Cal Set 75.2.

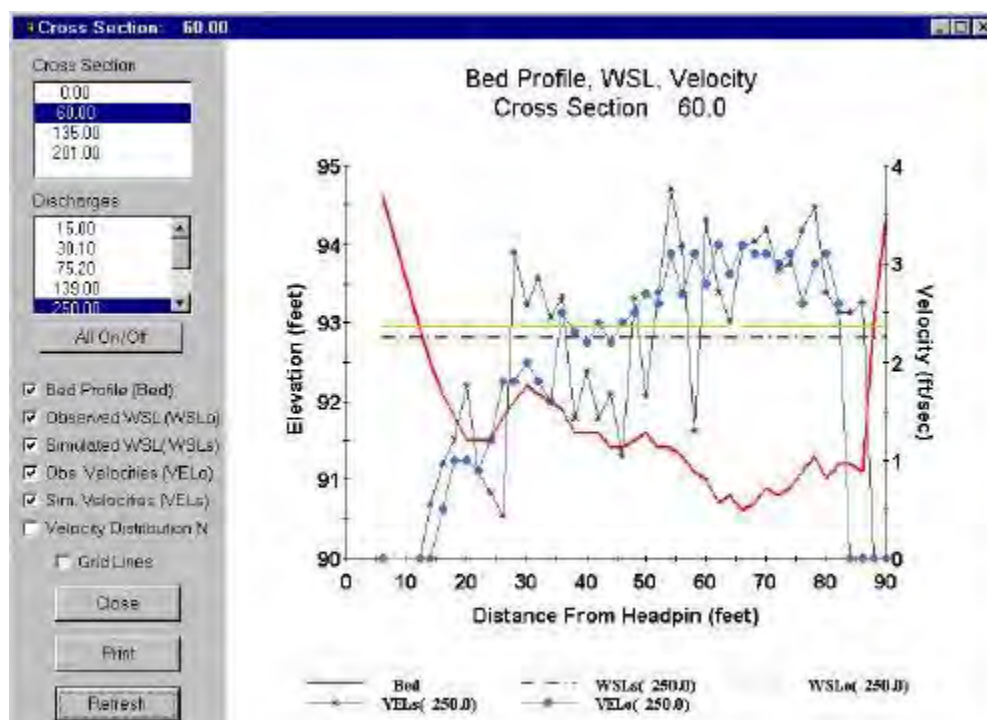


Figure L6-15. Simulated and observed velocity profile for 250 cfs at Xsec 60, Cal Set 75.2.

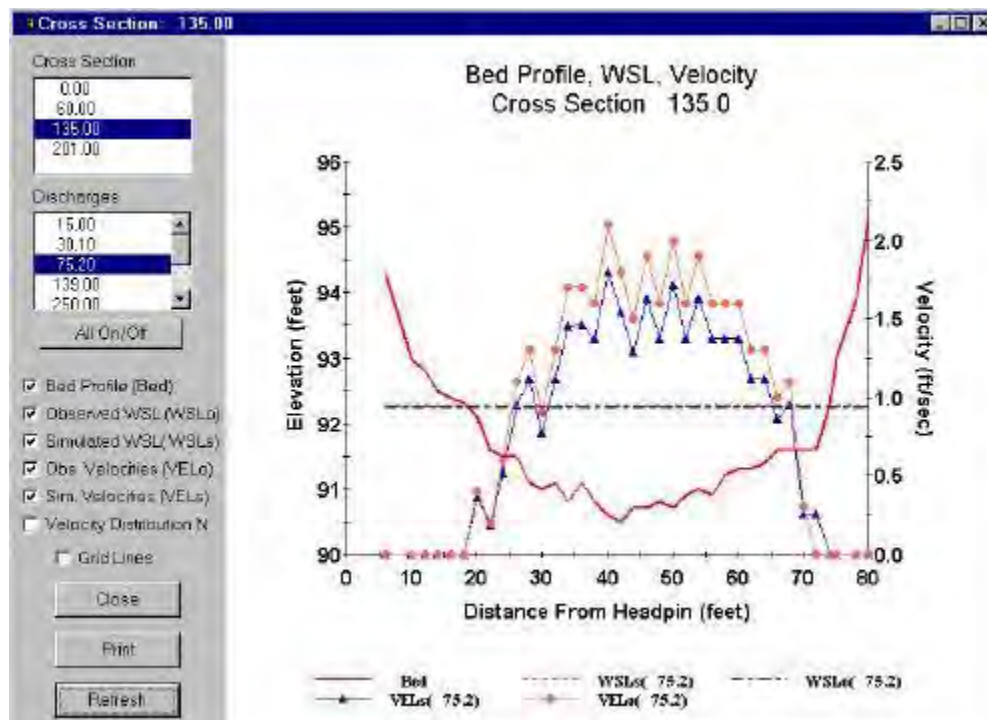


Figure L6-16. Simulated and observed velocity profile for 75.2 cfs at Xsec 135, Cal Set 75.2.

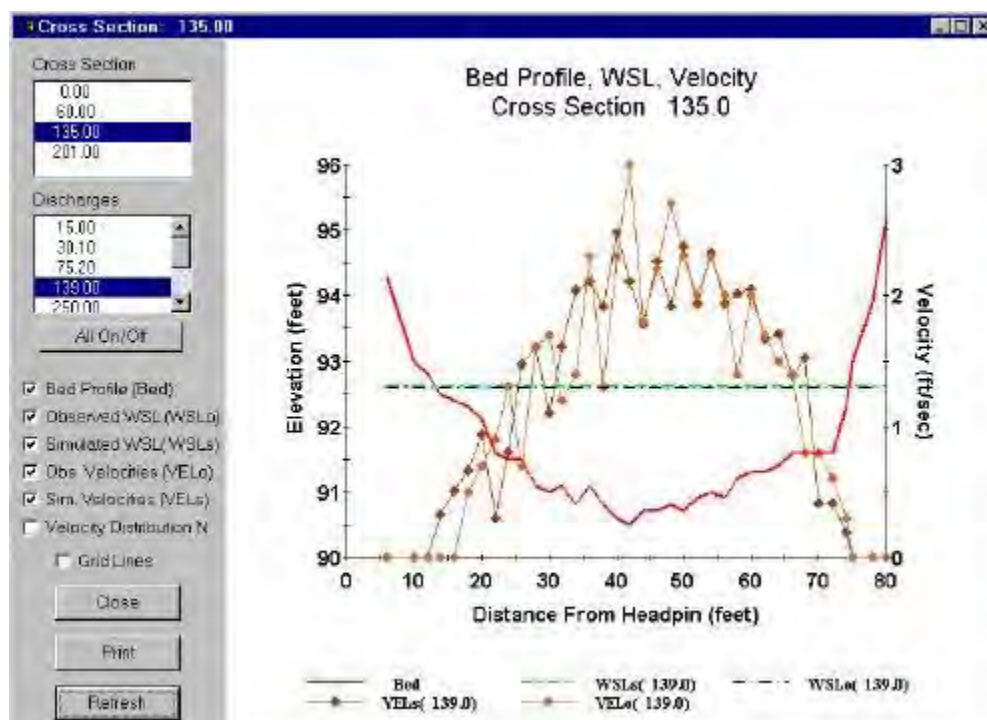


Figure L6-17. Simulated and observed velocity profile for 139 cfs at Xsec 135, Cal Set 75.2.

LABORATORY 6 –VELOCITY MODELING – VELSIM

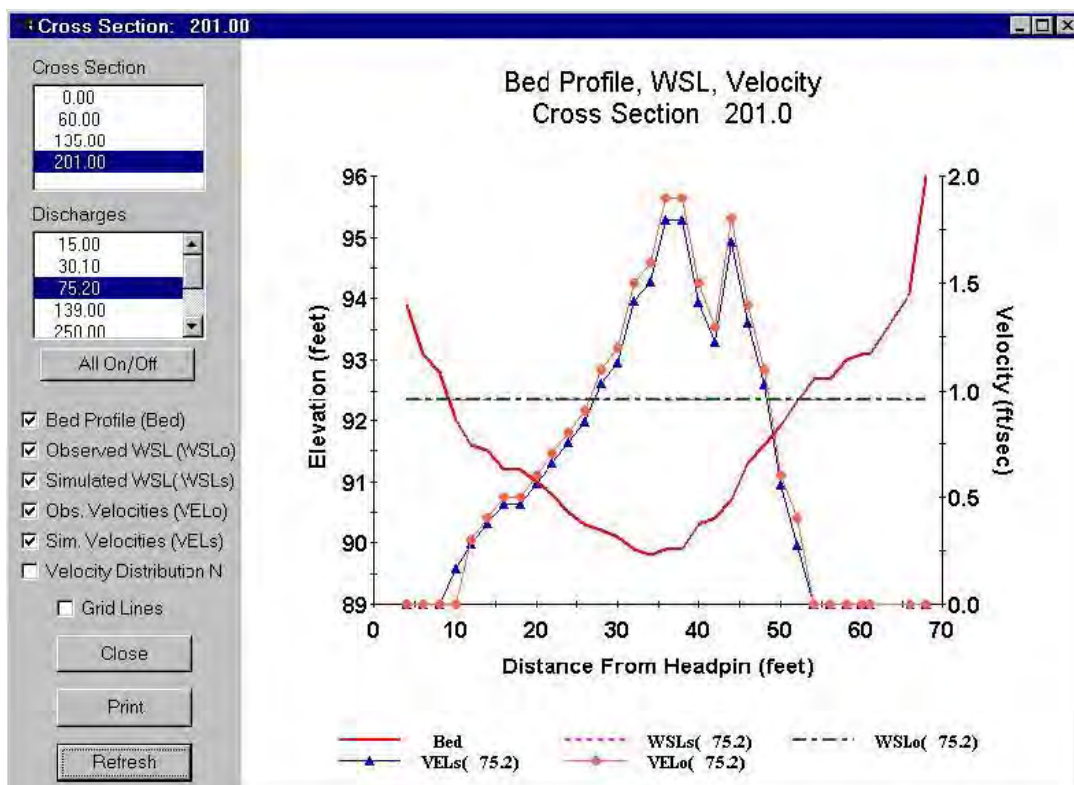
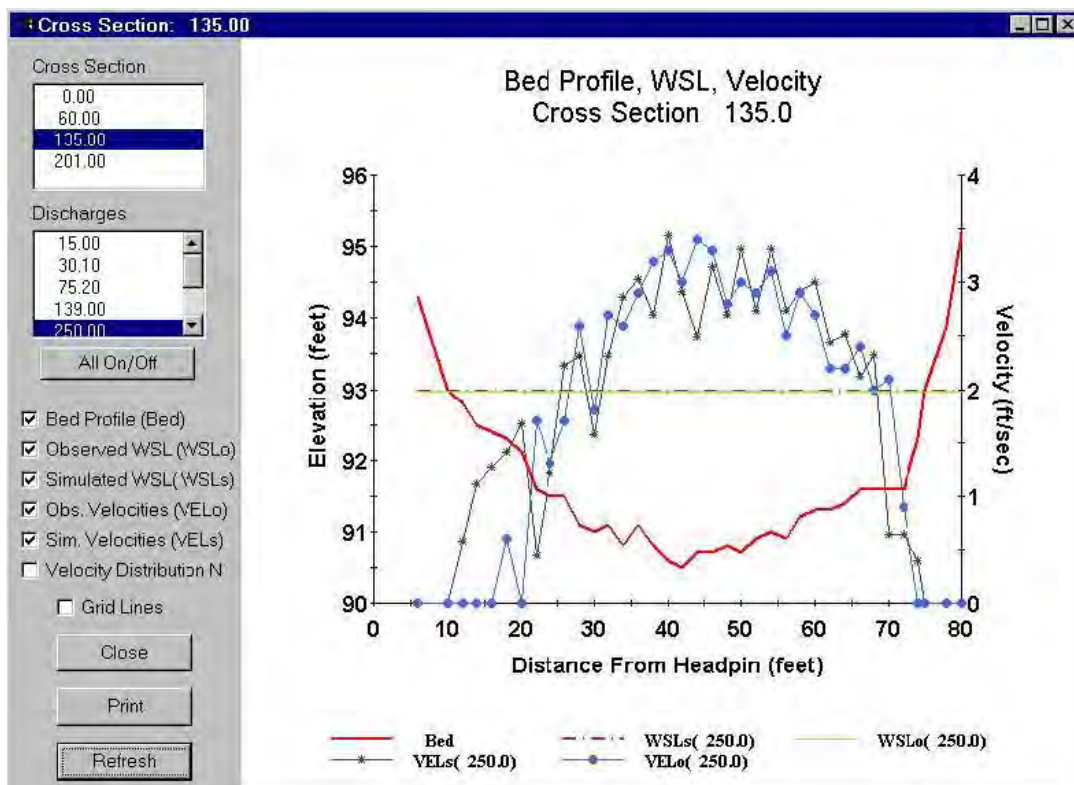


Figure L6-18. Simulated and observed velocity profile for 250 cfs at Xsec 135, Cal Set 75.2.

Figure L6-19. Simulated and observed velocity profile for 75.2 cfs at Xsec 201, Cal Set 75.2.

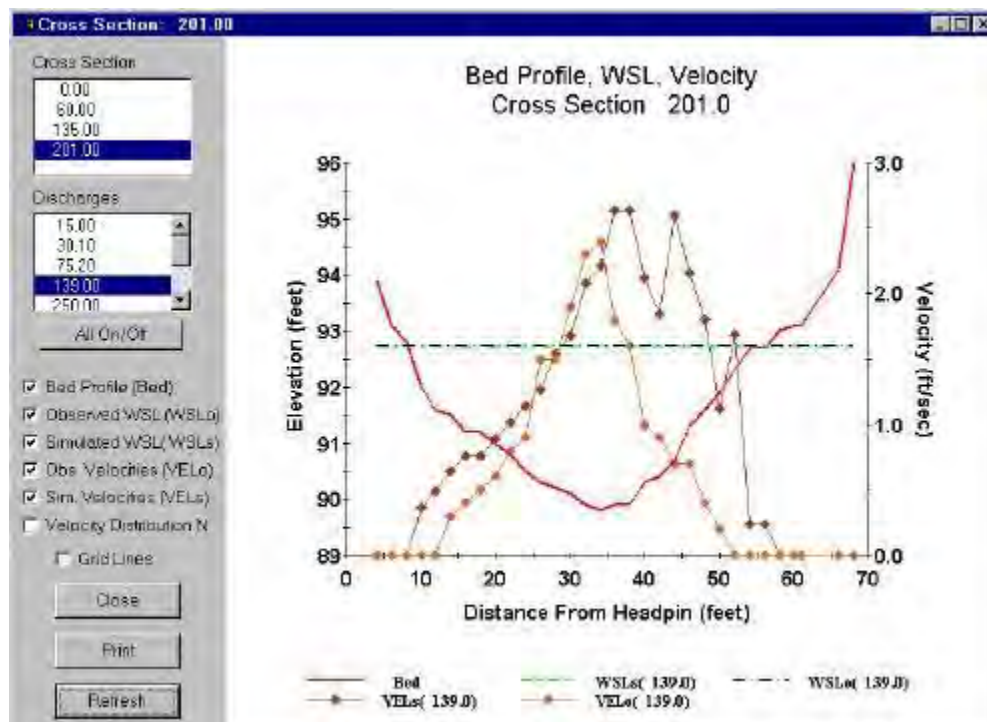


Figure L6-20. Simulated and observed velocity profile for 139 cfs at Xsec 201, Cal Set 75.2.

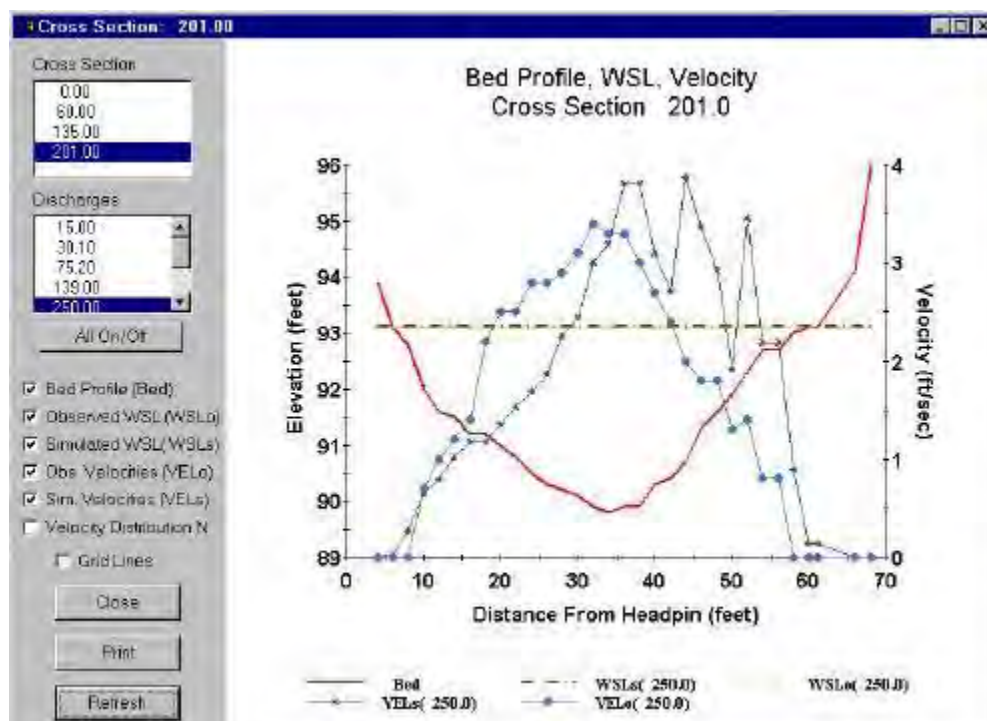


Figure L6-21. Simulated and observed velocity profile for 250 cfs at Xsec 201, Cal Set 75.2.

LABORATORY 6 –VELOCITY MODELING – VELSIM

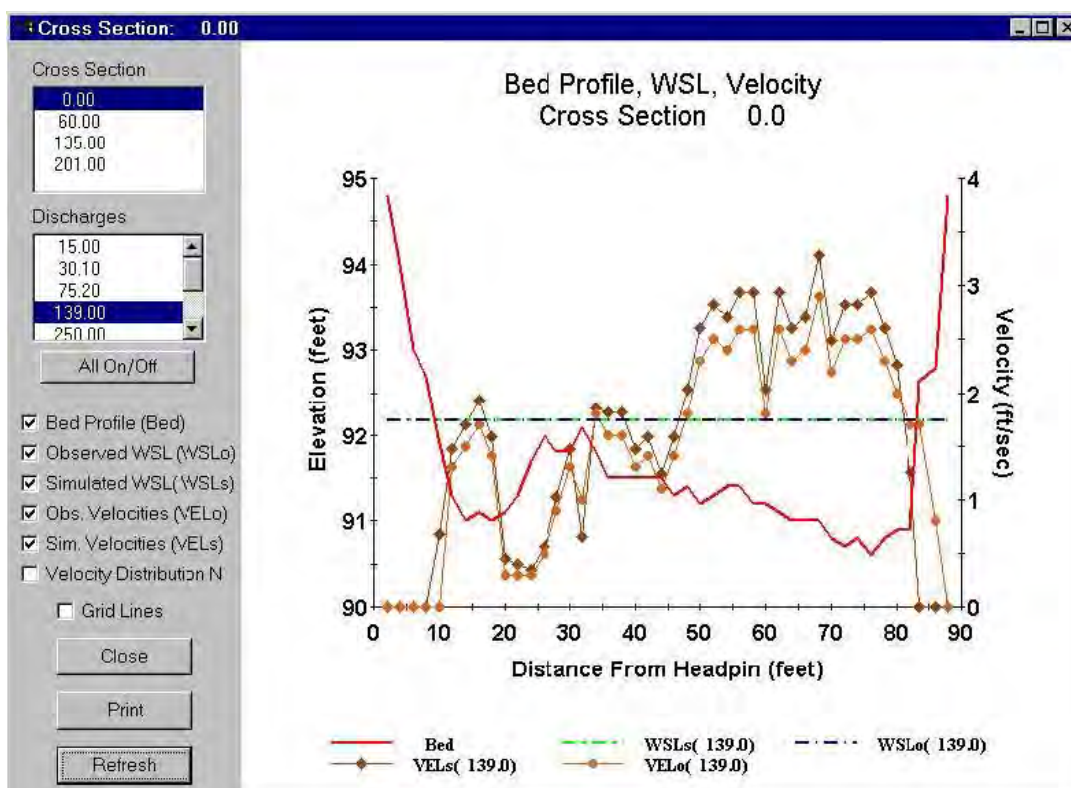
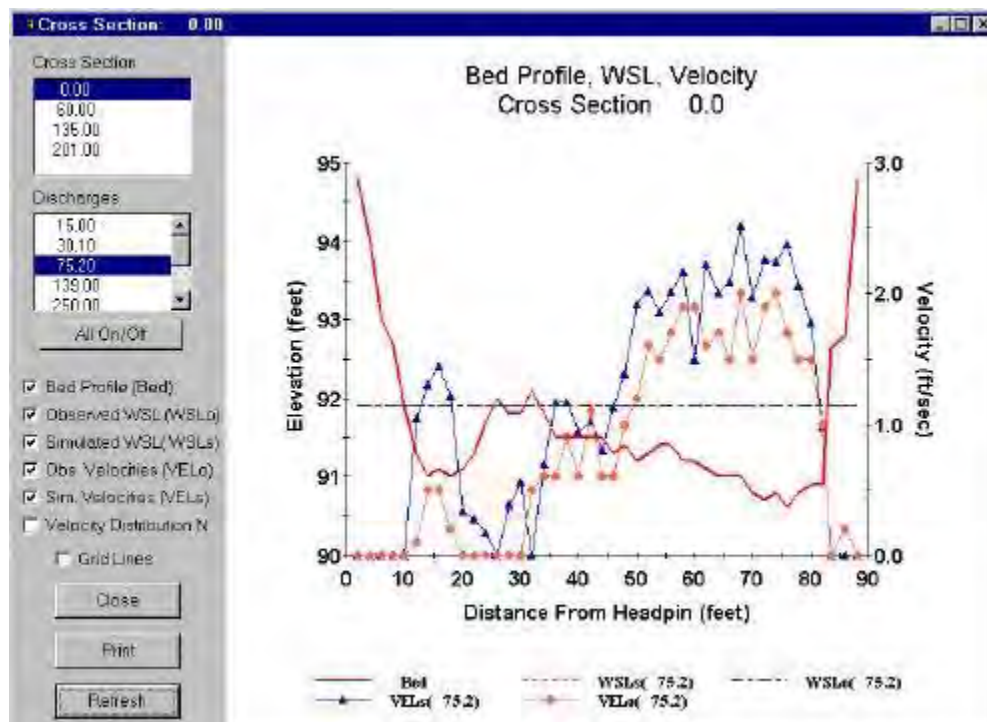


Figure L6-22. Simulated and observed velocity profile for 75.2 cfs at Xsec 0, Cal Set 139.

Figure L6-23. Simulated and observed velocity profile for 139 cfs at Xsec 0, Cal Set 139.

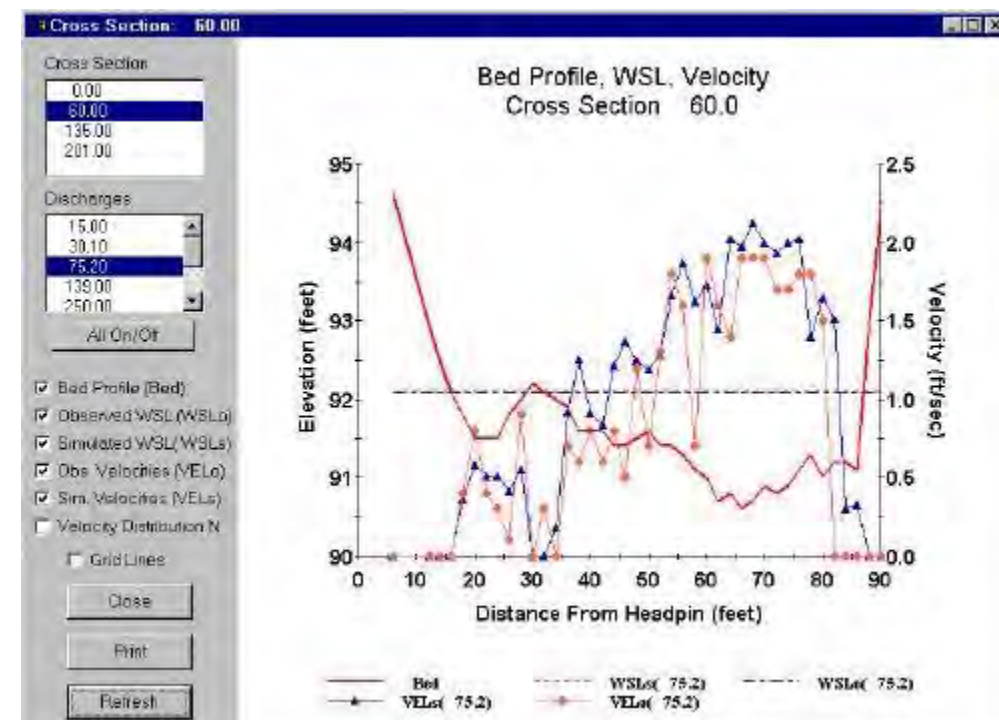
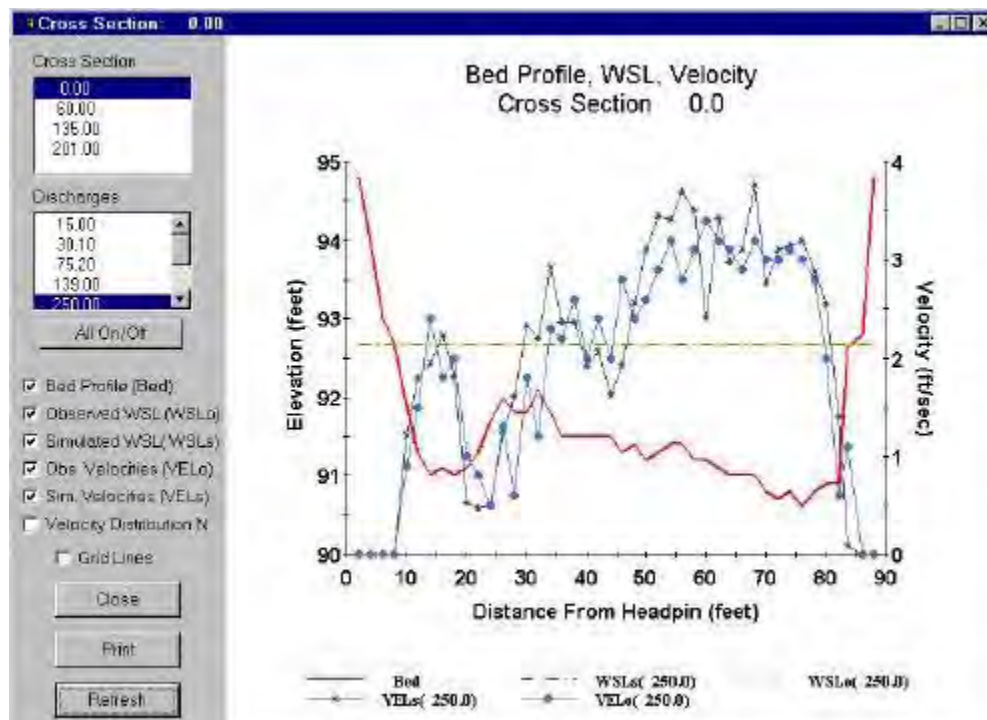


Figure L6-24. Simulated and observed velocity profile for 250 cfs at Xsec 0, Cal Set 139.

Figure L6-25. Simulated and observed velocity profile for 75.2 cfs at Xsec 60, Cal Set 139.

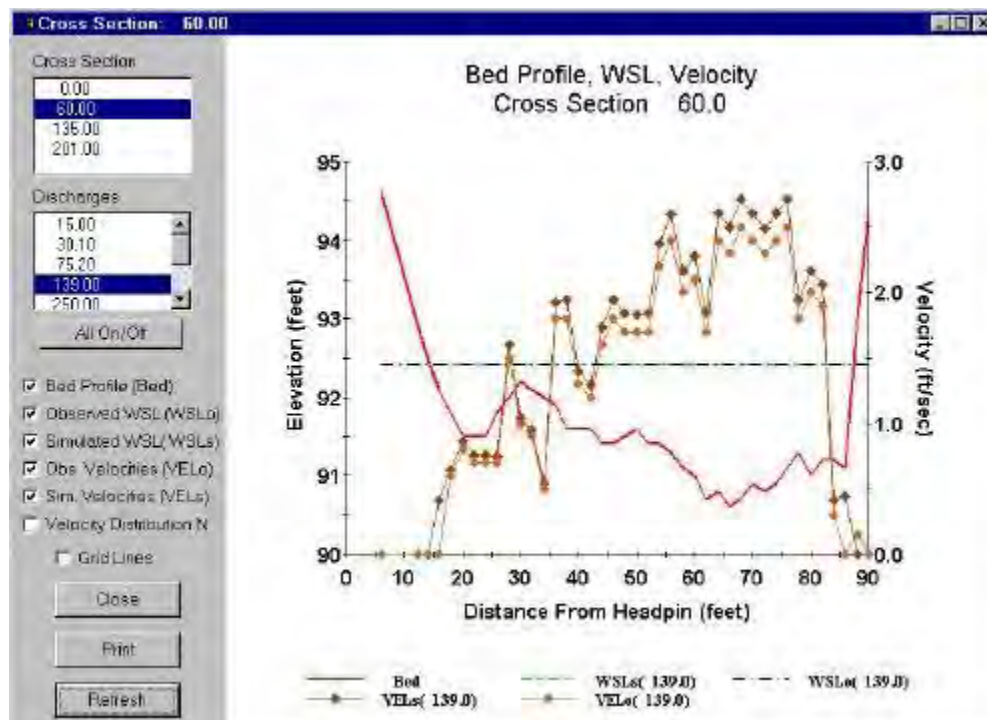


Figure L6-26. Simulated and observed velocity profile for 139 cfs at Xsec 60, Cal Set 139.

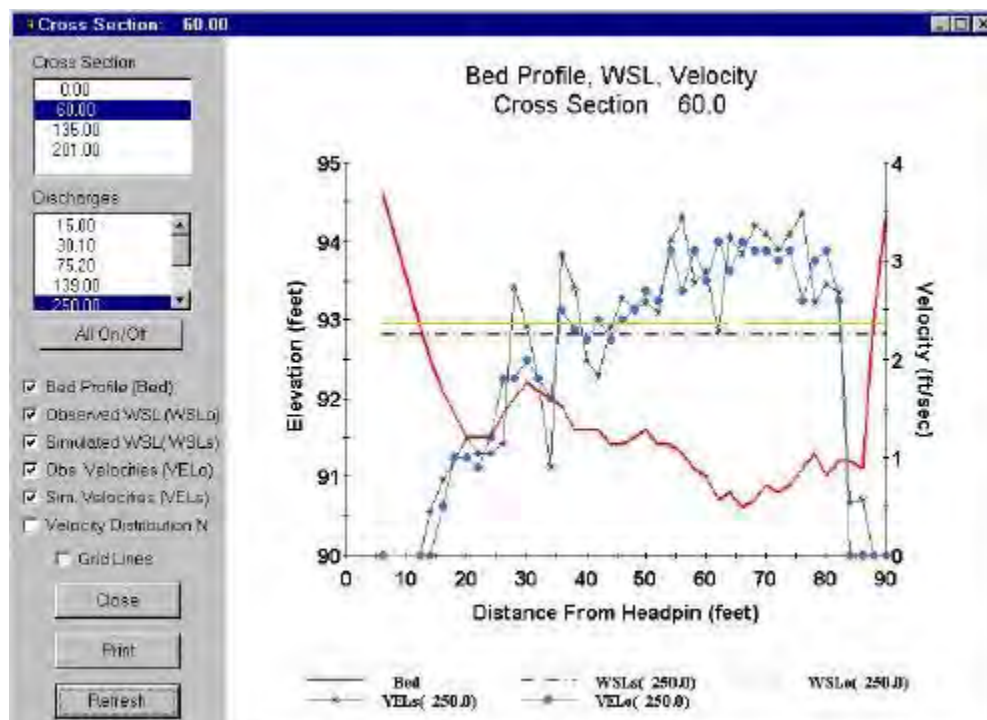


Figure L6-27. Simulated and observed velocity profile for 250 cfs at Xsec 60, Cal Set 139.

LABORATORY 6 –VELOCITY MODELING – VELSIM

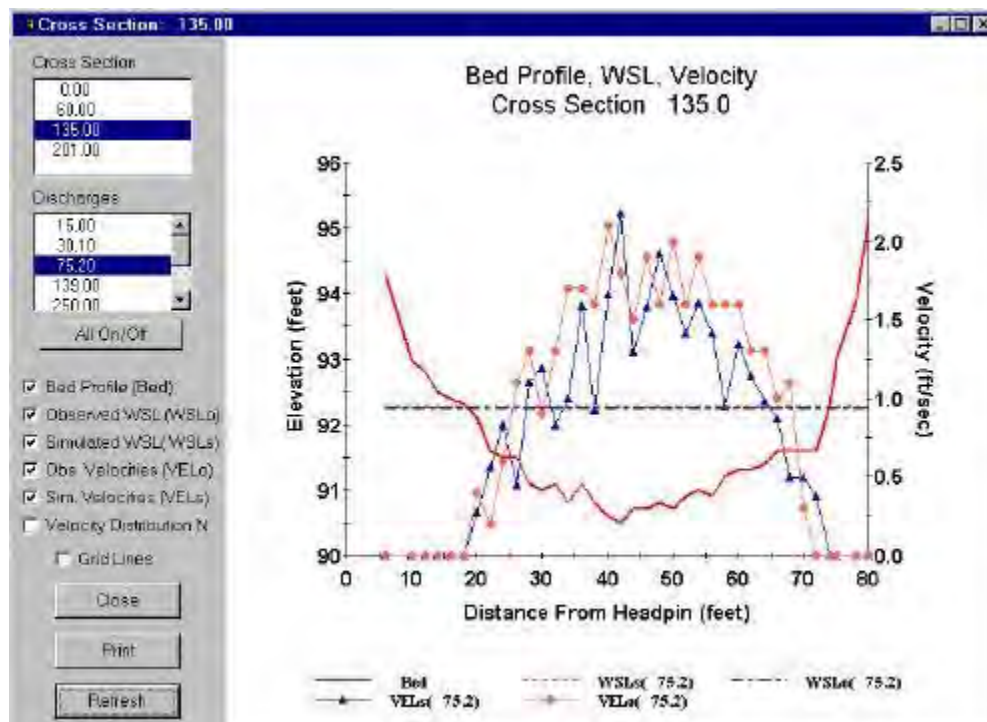


Figure L6-28. Simulated and observed velocity profile for 75.2 cfs at Xsec 135, Cal Set 139.

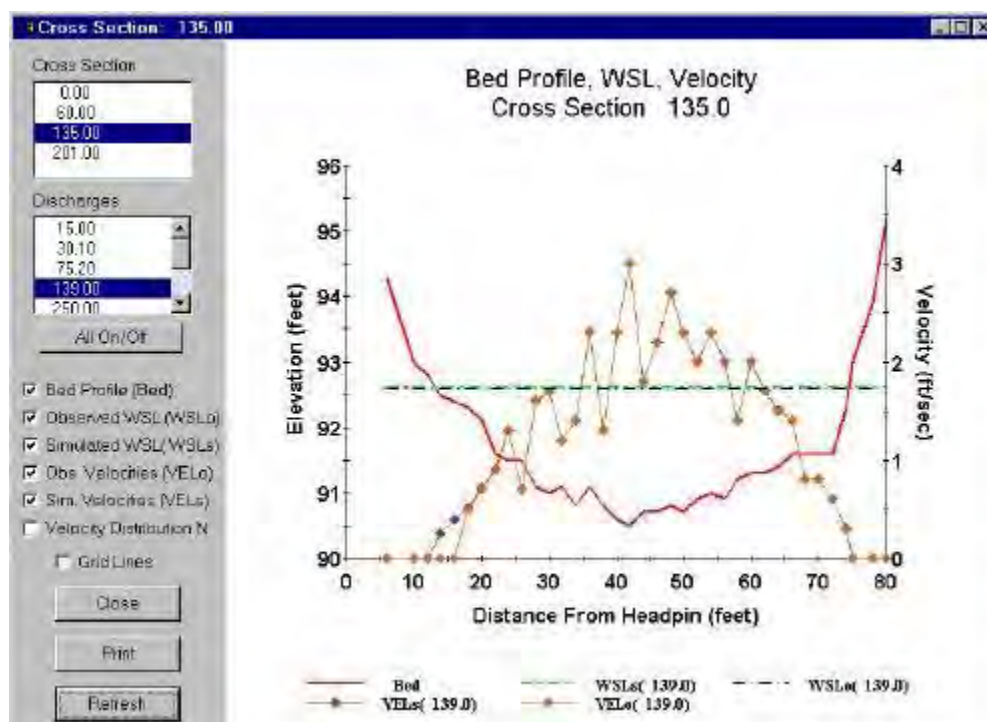


Figure L6-29. Simulated and observed velocity profile for 139 cfs at Xsec 135, Cal Set 139.

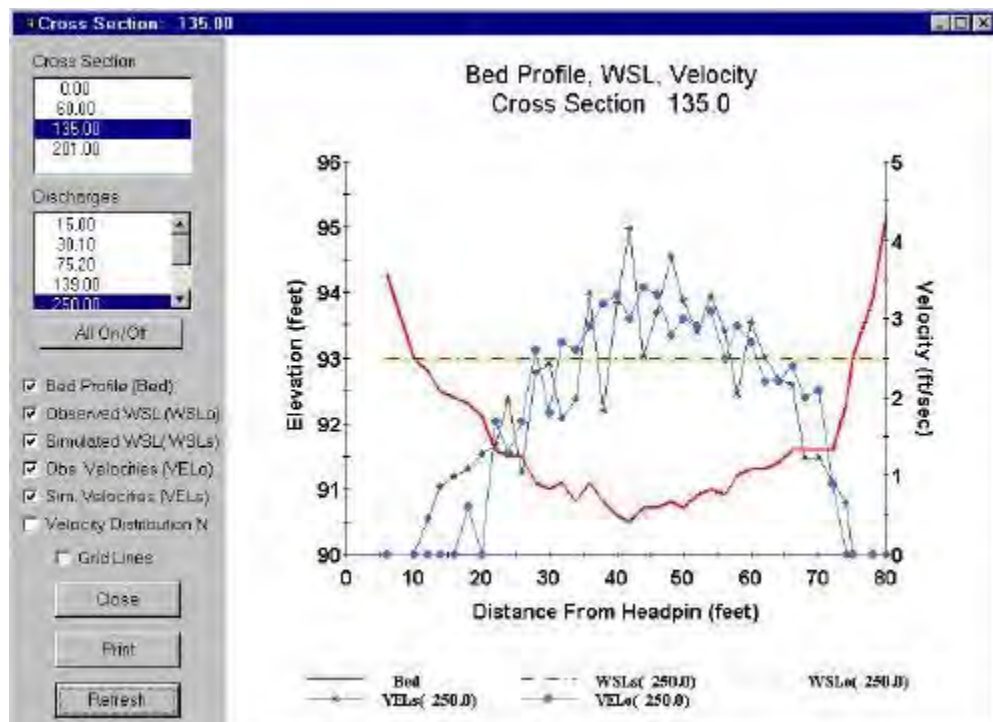


Figure L6-30. Simulated and observed velocity profile for 250 cfs at Xsec 135, Cal Set 139.

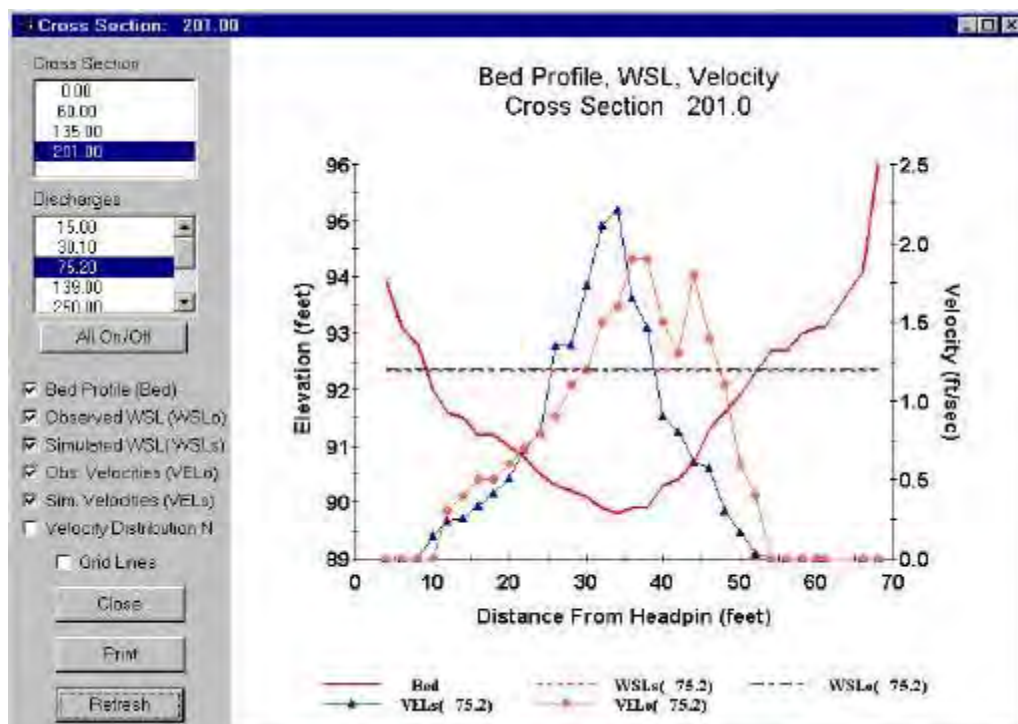


Figure L6-31. Simulated and observed velocity profile for 75.2 cfs at Xsec 201, Cal Set 139.

LABORATORY 6 –VELOCITY MODELING – VELSIM

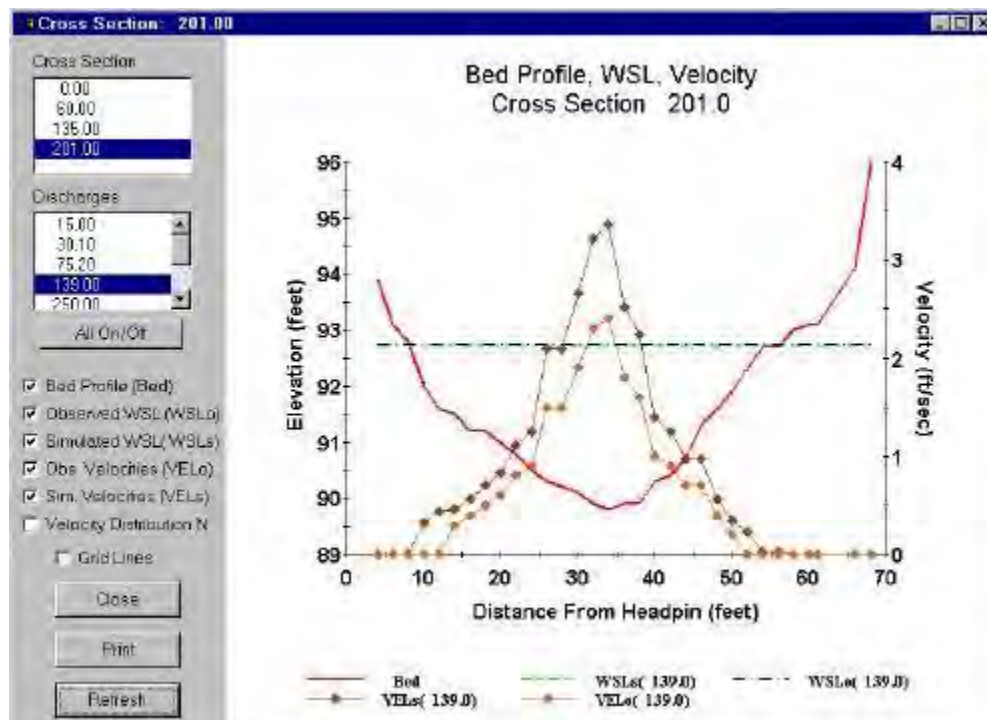


Figure L6-32. Simulated and observed velocity profile for 139 cfs at Xsec 201, Cal Set 139.

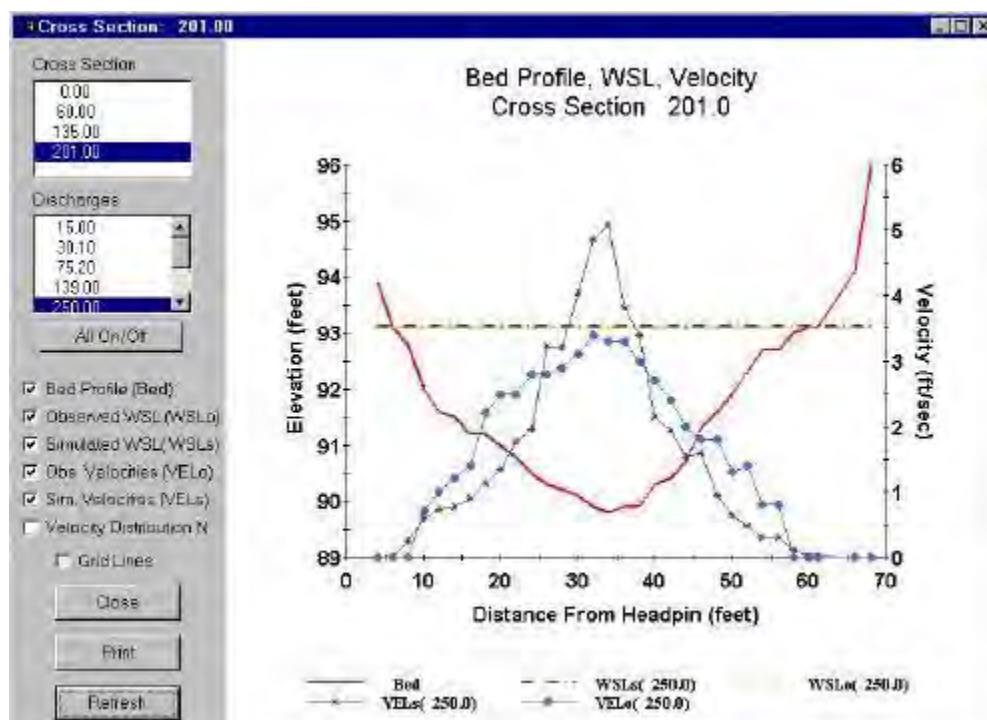


Figure L6-33. Simulated and observed velocity profile for 250 cfs at Xsec 201, Cal Set 139.

LABORATORY 6 –VELOCITY MODELING – VELSIM

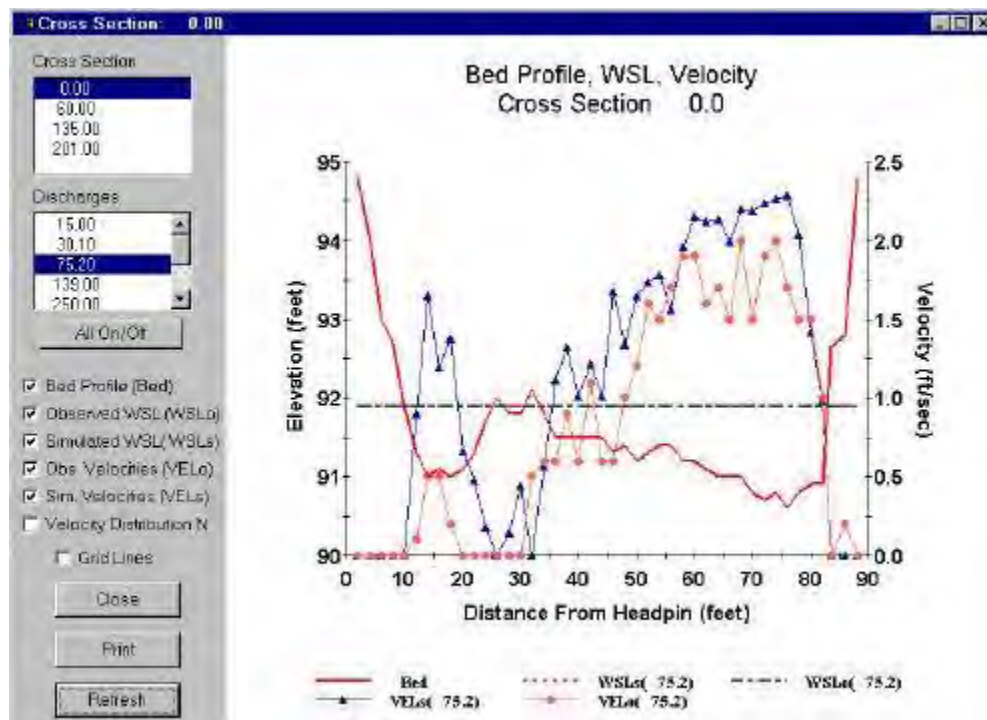


Figure L6-34. Simulated and observed velocity profile for 75.2 cfs at Xsec 0, Cal Set 250.

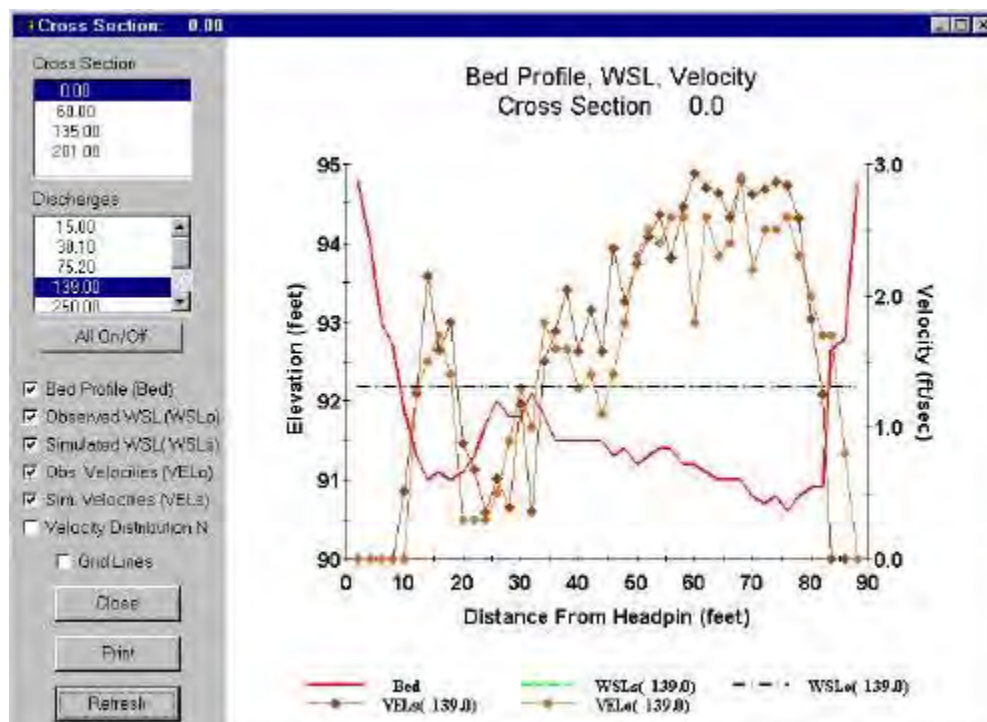


Figure L6-35. Simulated and observed velocity profile for 139 cfs at Xsec 0, Cal Set 250.

LABORATORY 6 –VELOCITY MODELING – VELSIM

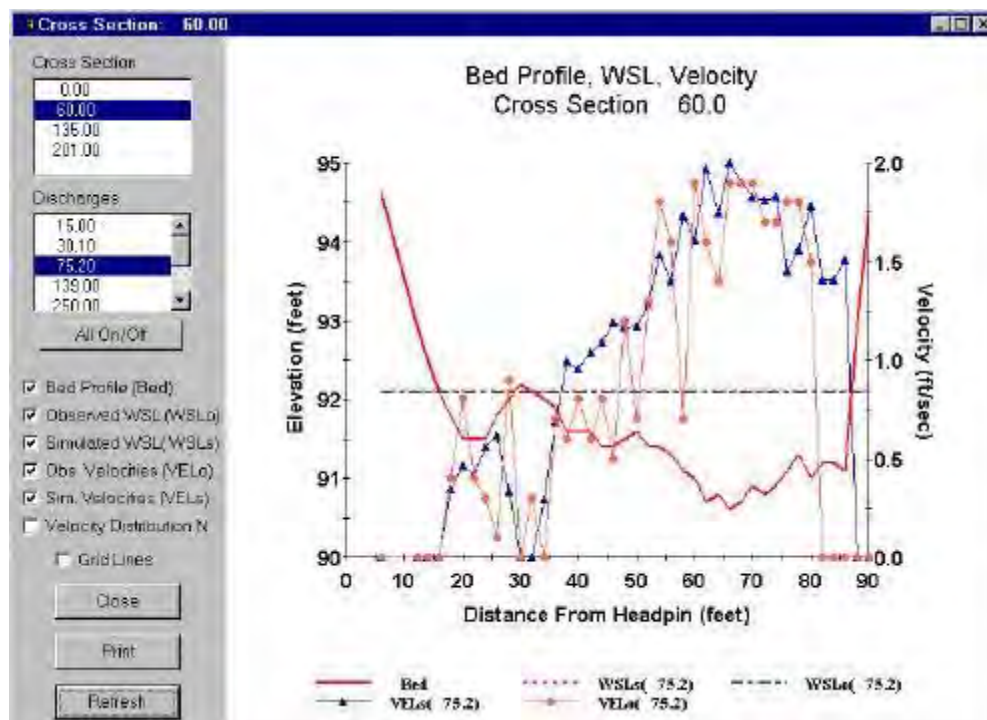
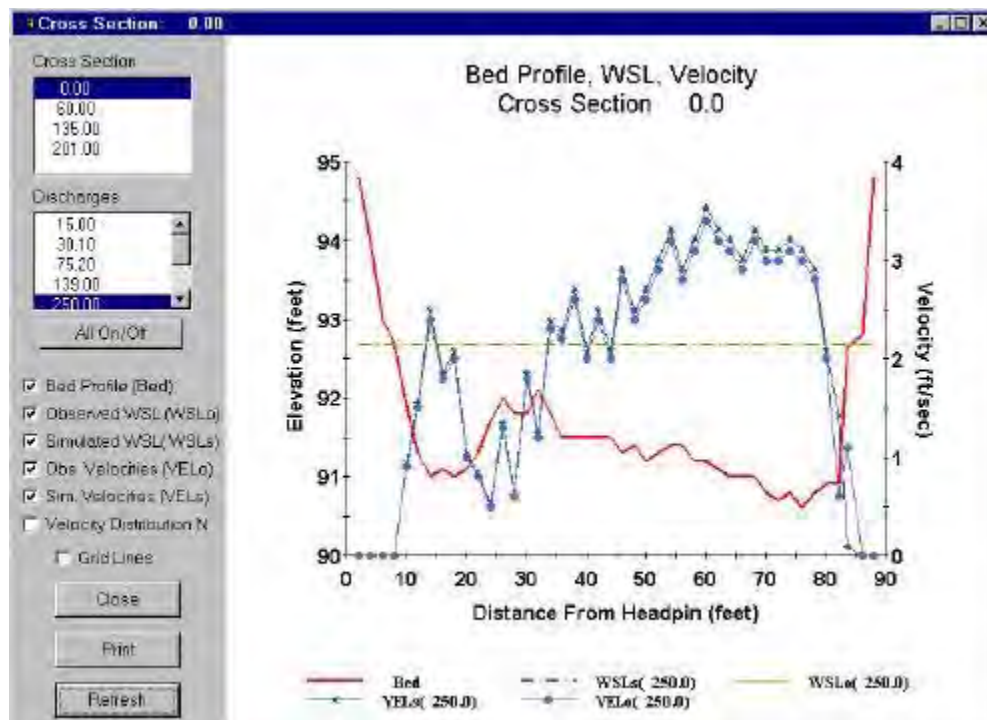


Figure L6-36. Simulated and observed velocity profile for 250 cfs at Xsec 0, Cal Set 250.

Figure L6-37. Simulated and observed velocity profile for 75.2 cfs at Xsec 60, Cal Set 250.

LABORATORY 6 –VELOCITY MODELING – VELSIM

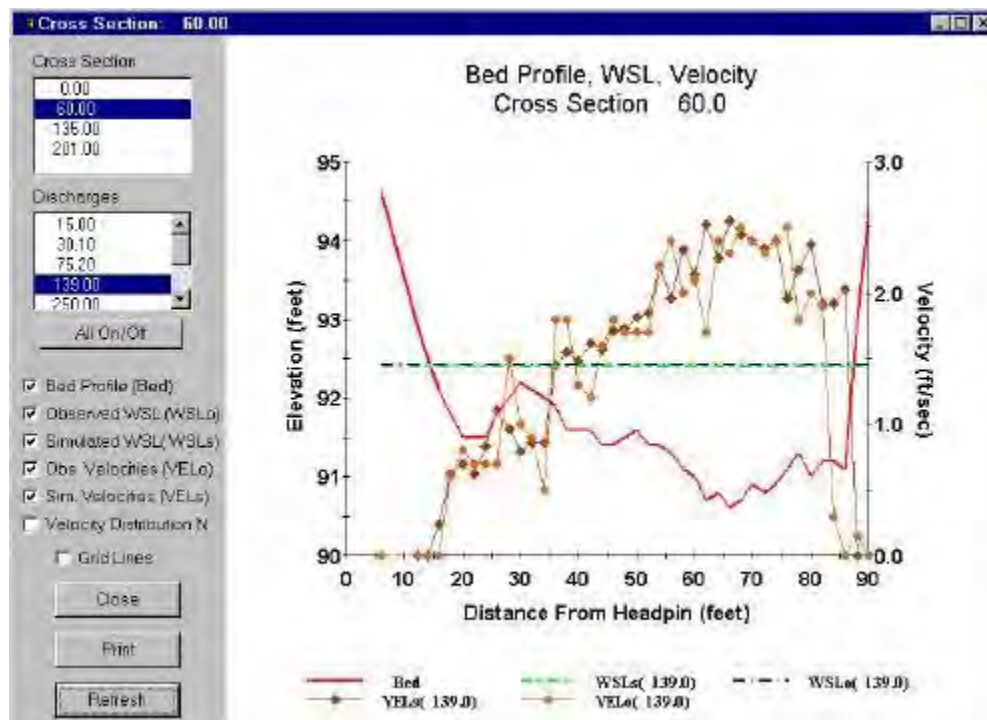


Figure L6-38. Simulated and observed velocity profile for 139 cfs at Xsec 60, Cal Set 250.

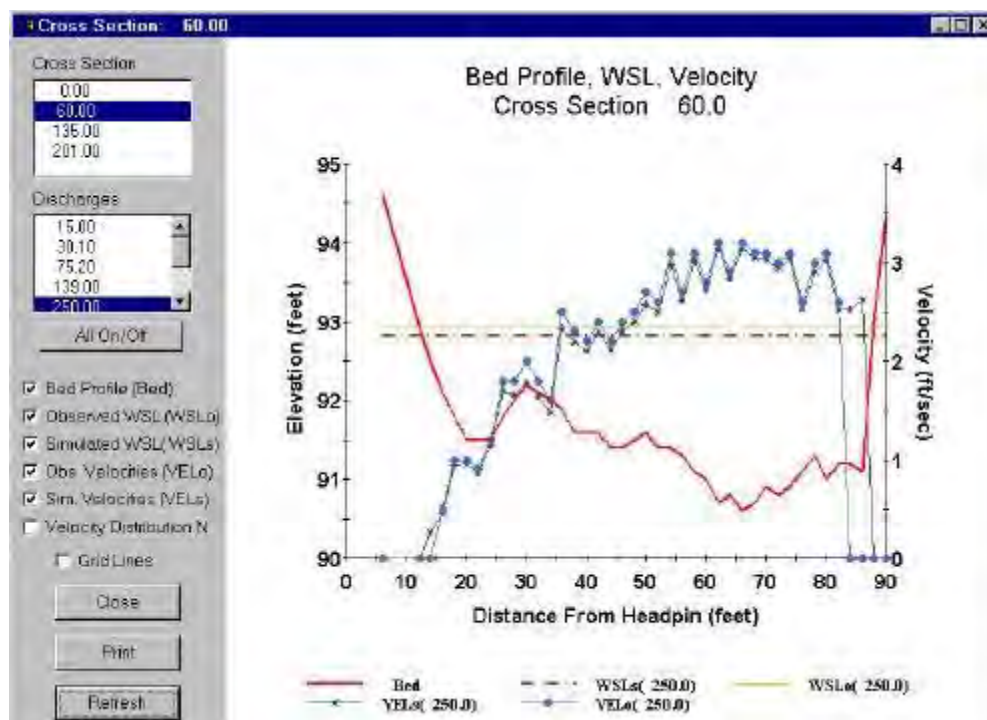


Figure L6-39. Simulated and observed velocity profile for 250 cfs at Xsec 60, Cal Set 250.

LABORATORY 6 –VELOCITY MODELING – VELSIM

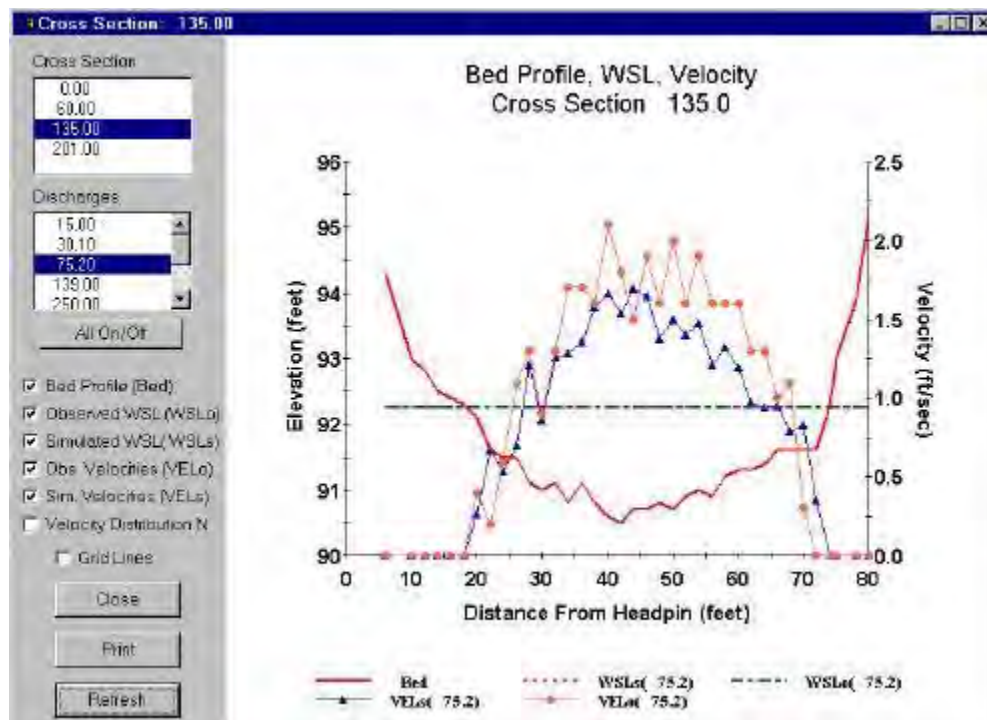


Figure L6-40. Simulated and observed velocity profile for 75.2 cfs at Xsec 135, Cal Set 250.

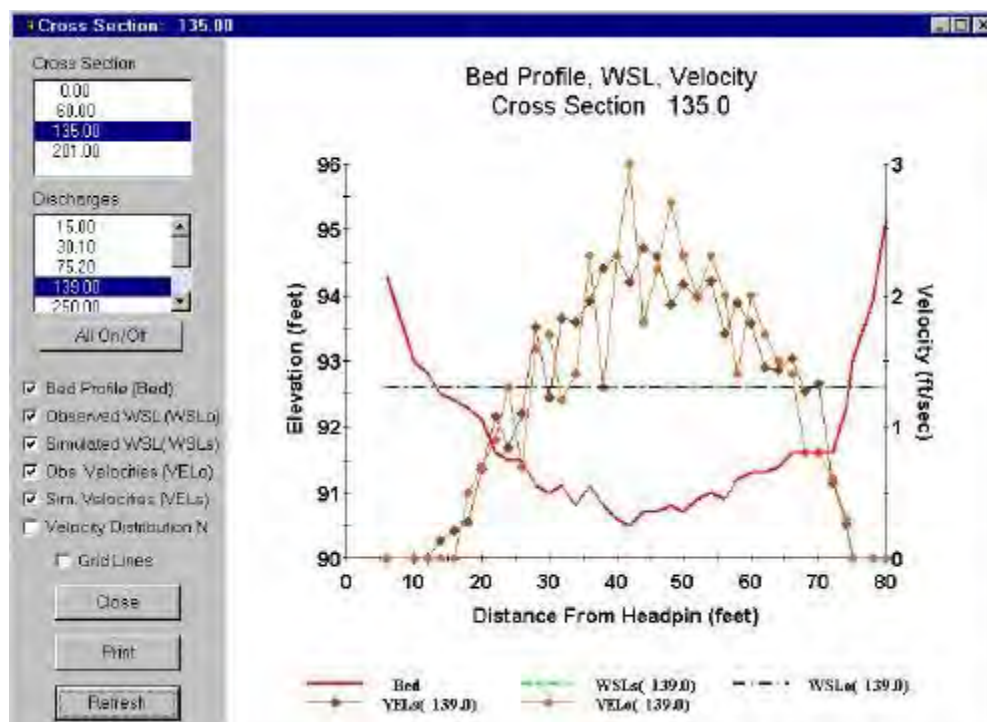


Figure L6-41. Simulated and observed velocity profile for 139 cfs at Xsec 135, Cal Set 250.

LABORATORY 6 –VELOCITY MODELING – VELSIM

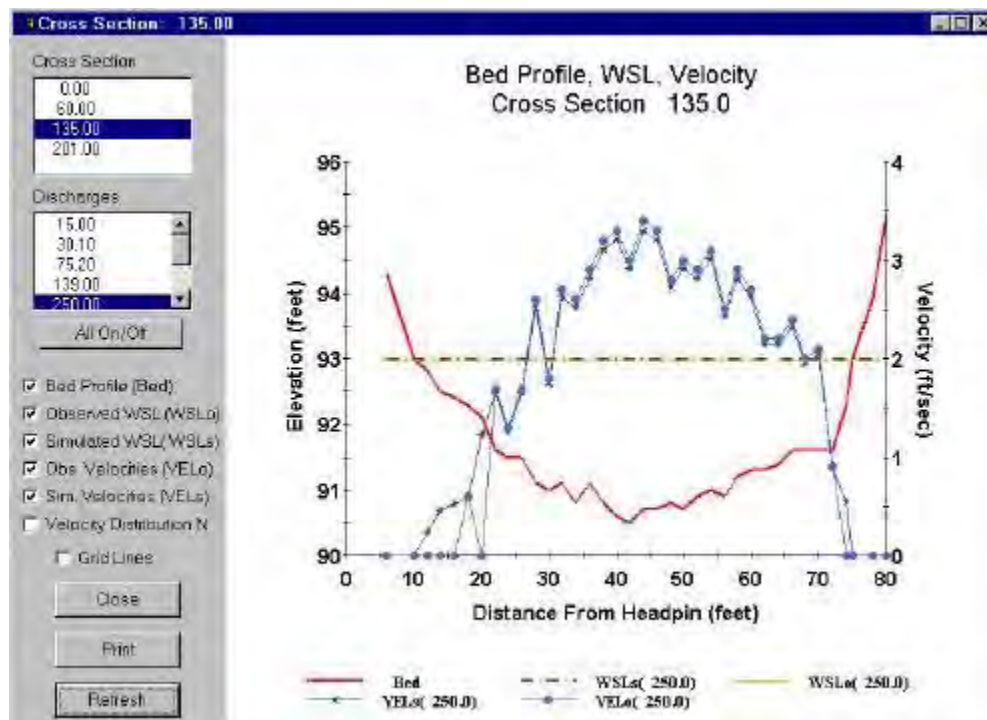


Figure L6-42. Simulated and observed velocity profile for 250 cfs at Xsec 135, Cal Set 250.

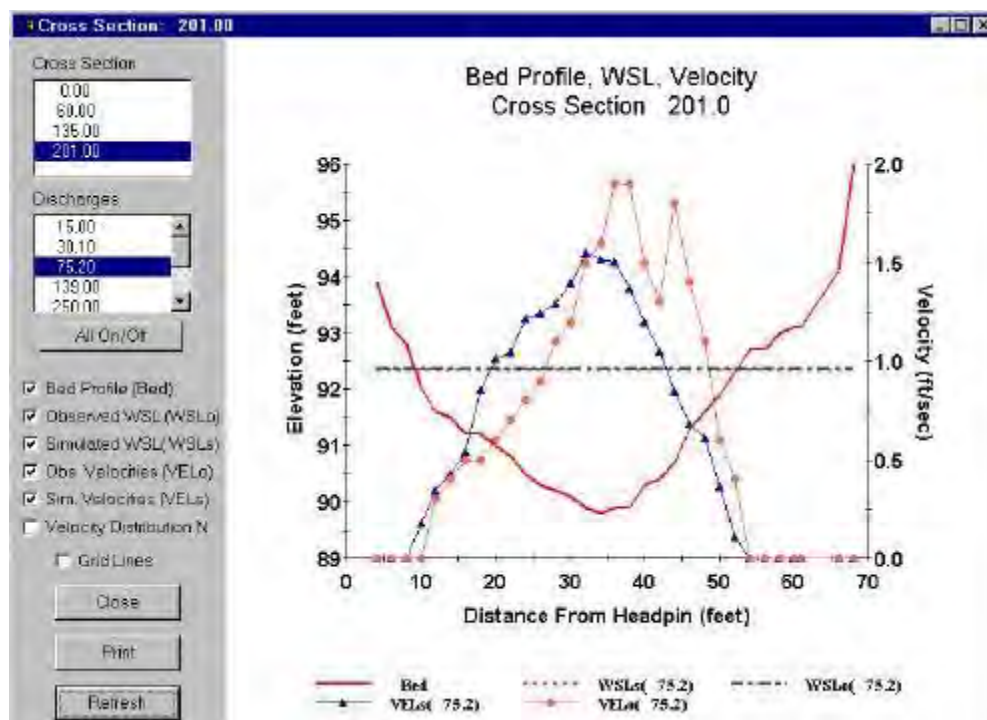


Figure L6-43. Simulated and observed velocity profile for 75.2 cfs at Xsec 201, Cal Set 250.

LABORATORY 6 –VELOCITY MODELING – VELSIM

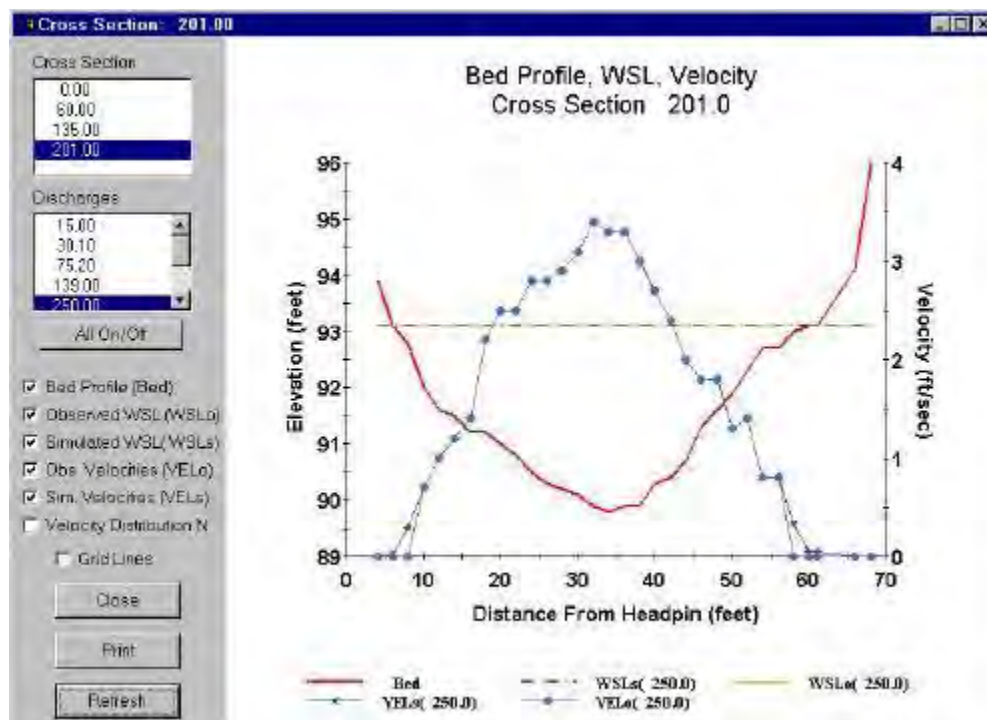
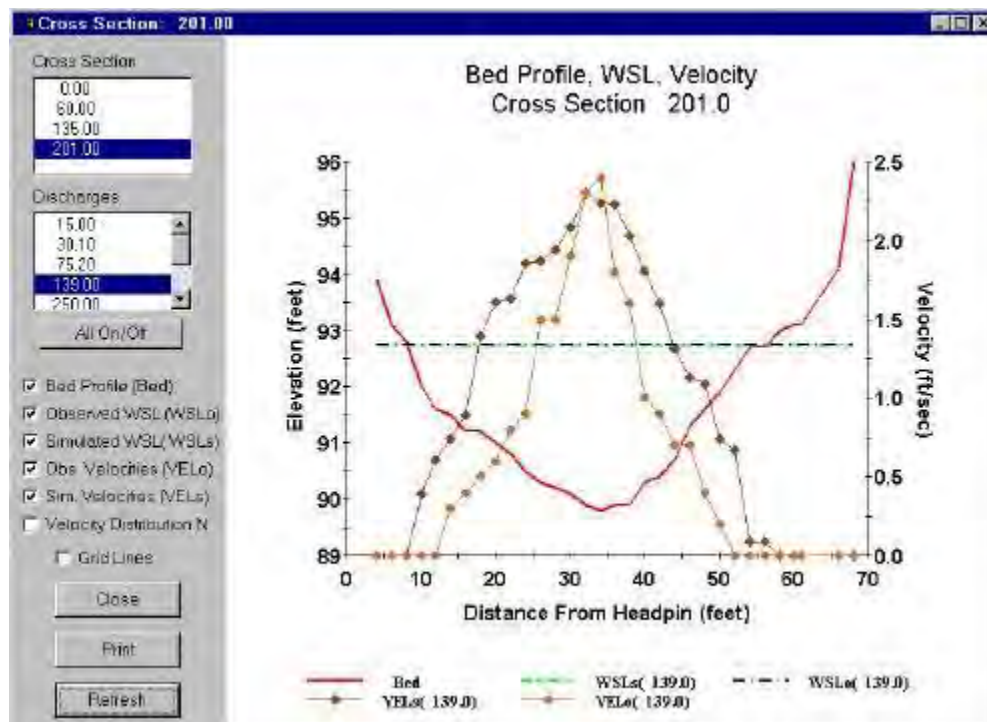


Figure L6-44. Simulated and observed velocity profile for 139 cfs at Xsec 201, Cal Set 250.

Figure L6-45. Simulated and observed velocity profile for 250 cfs at Xsec 201, Cal Set 250.

LABORATORY 6 –VELOCITY MODELING – VELSIM

Laboratory 7. Habitat Suitability Criteria in PHABSIM

Objective

The objective of this laboratory is to introduce the use of habitat suitability criteria (HSC) within the PHABSIM for Windows system. The laboratory will illustrate the method used to input HSC for use within PHABSIM and examine several of the available criteria maintenance programs.

Data Files Used: Lab7.phb, Curvlib.phb

Introduction

The principal means by which PHABSIM integrates biological information for habitat modeling purposes is through the use of HSC (sometimes referred to as suitability-of-use criteria) within the various habitat models. The laboratory will not deal with the specifics of HSC development. However, the various means by which HSC can be entered and manipulated within PHABSIM will be examined. See Bovee et al. (1998) for a detailed description of HSC and their development.

In PHABSIM, HSC data are created, edited, and stored in the **\Edit\Suitability Curves** section of the program. These data contain the HSC coordinate data for species and life stages in terms of depth, velocity, channel index, and temperature.

HSCs for a particular species and life stage are typically grouped into three sets of HSC data representing the relationships between depth, velocity, and channel index and their corresponding suitability values.

In PHABSIM, HSC data are referenced by HSC numbers. Although these HSC numbers can be arbitrarily assigned within any PHABSIM project file, the structure of the numbers does control the format of the output results from the habitat programs as will be discussed later in this lab. The steps in this lab are designed to build basic skill in using HSC w/in PHABSIM.

Step 1. HSC Numbering

HSC numbering within PHABSIM allows the user to organize HSC curves by species groups. The basic format for HSC numbering is:

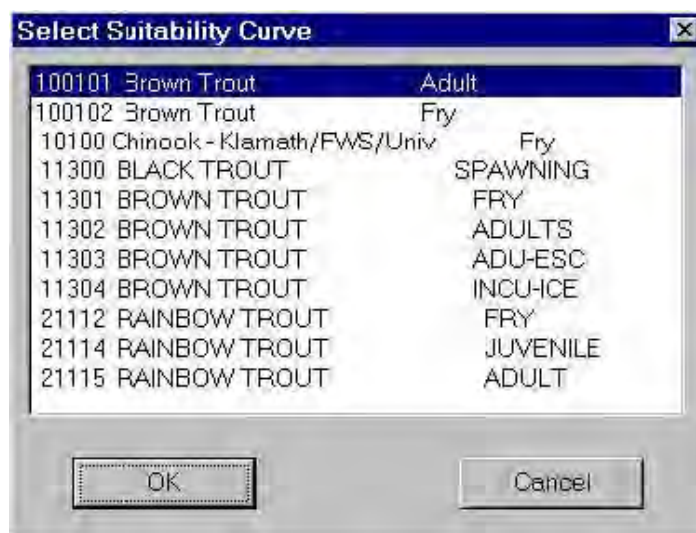
xxxxyy

The first four digits (i.e., xxxx) denote the >species=, while the last two digits (i.e., yy) denote the >life stage=. Figure L7-1 contains a list of habitat suitability criteria for use in a particular study. This list is obtained by clicking **\Edit\Suitability Curves\Curves\Select by ID**.

The **Graph** button in the **\Edit\Suitability Curves** window allows you to view individual habitat suitability criteria graphically. To view all HSC for a species/life stage, select **Display All Graphs** in the **\Edit\Suitability Curves\Curves** menu. Figure L7-2 shows an example of the resulting plot. Note that there are no temperature HSC values in this curve set for Black Trout.

Figure L7-1. List of showing species and life

Note that each HSC set and channel index) is unique HSC number for stage. In the example should identify that has a HSC number of 21114, on the other hand, Rainbow Trout Juvenile you recognize how this numbering convention



suitability curves stage numbering.

(i.e., velocity, depth, associated with a each species and life above, the user Rainbow Trout Fry 21112. HSC number identifies the curve set. Be sure follows the described above.

Step 2: HSC Data PHABSIM

Structure in

Move to **\Edit\Suitability Curves** in the SAMPLE.phb project and click **Select\By ID**. This displays a list (as in Figure L7-1) of the HSC curves that have been entered in the sample project including curve number, species, and life stage. New curves are entered by clicking the **\Edit\Suitability Curves\File** menu item, selecting **New Curve**, then filling in the boxes for Curve number, Species, and Life stage. Enter the HSC values in the table shown in that window (the first table is velocity). To change from velocity to depth, channel index or temperature, click the appropriate radio button in the **Curve Type** box to the upper right. Click the desired radio button (i.e., depth) and enter the HSC values in the table. Be sure to fill in all HSC tables before exiting. Habitat suitability criteria are discussed in Chapter 3 of the manual. Remember the PHABSIM convention that all HSC curves must begin at 0 and end at 100. In most situations the starting and starting values will be 0.0, 0.0 and ending values will be 100.0, 0.0. When might this not be the case?

In the suitability curve-editing portion of our Sample project, select Rainbow Trout Fry and note that the first velocity coordinate point at a velocity of 0.0 has a suitability value of 1.00. Note the last value. Again, failure to include the coordinate points with 100 for all curve sets will result in an error message indicating that the 100 value has not been entered. You cannot exit HSC data entry until all curves have final values of 100.

While in the **\Edit\Suitability Curves** window, each HSC set can be viewed graphically by clicking the **Graph** button. For Rainbow Trout fry, the HSC value of velocity descends from 1.0 at a velocity of 0.0 to 0.0 at a velocity of 0.5. For more complicated HSC graphs, using the zoom feature may enhance viewing of particular portions of the curve. The graph automatically updates when a different curve is selected. For example: click **Graph** and drag the plot to the lower right so the **Curve** box with radio buttons is revealed. Then click the **Depth** (or any other) radio button. The graph will update to show the depth curve at the same degree of zoom that was previously selected.

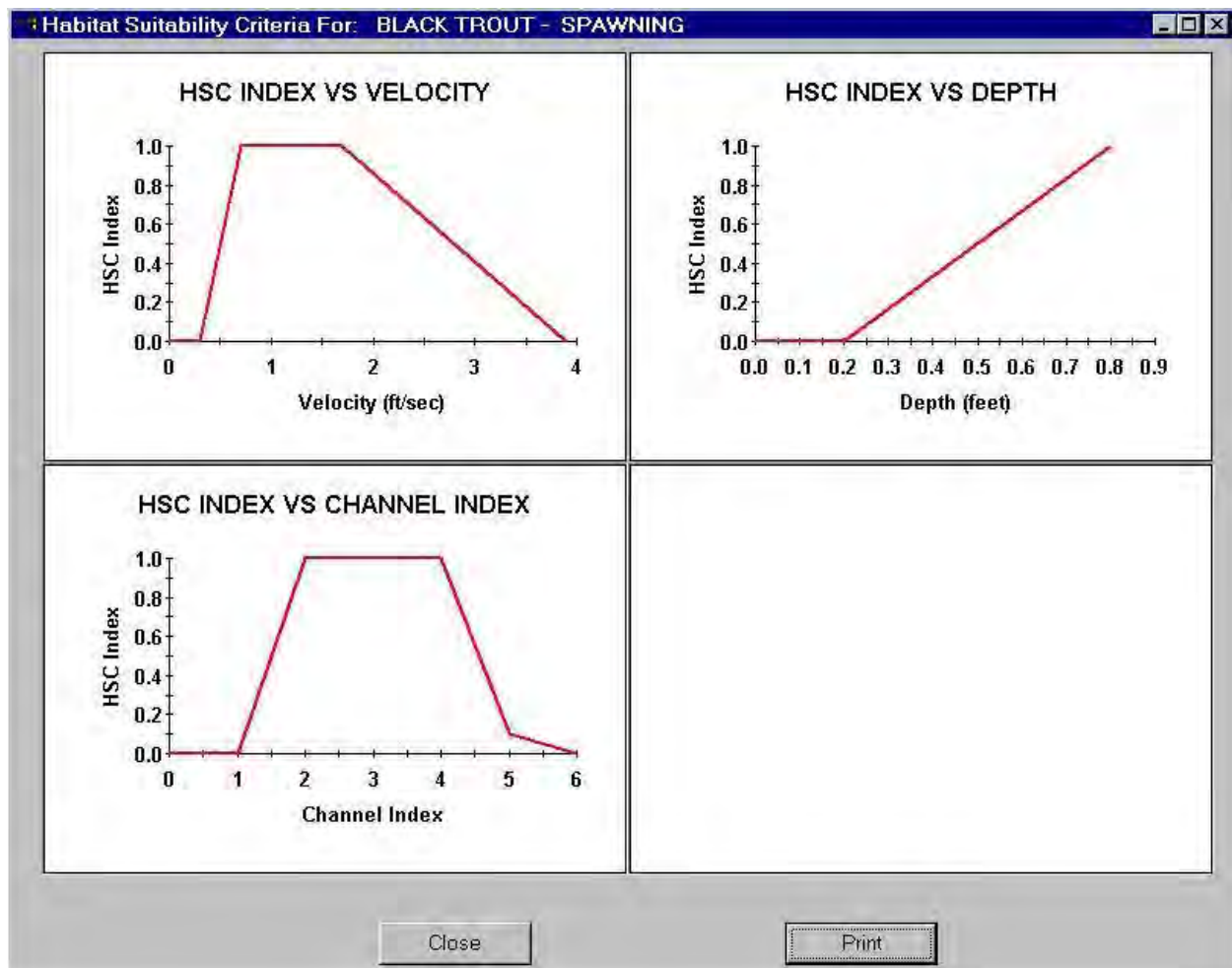


Figure L7-2. An example of displaying all HSC for a selected species and life stage.

When you are finished entering or viewing HSC curves, click **OK** to exit the **\Edit\Suitability Curves** window.

Step 3. Building HSC Libraries

The **\Edit\Suitability Curves** section of PHABSIM can be used for entering HSC data to create a set of HSC curves. Users of PHABSIM Version 2.0 (DOS) will recall the term FISHCRV libraries applied to such HSC sets. Table L7-1 lists HSC coordinate data for Brown Trout adult and fry for velocity, depth, and channel index which will be used to construct HSC data. The HSC numbers for each species and life stage are also indicated in this table.

Table L7-1. Brown trout adult and fry HSC ID numbers and criteria coordinates.

Brown Trout - Adult HSC ID Number: 100101

Velocity SI Depth SI Channel Index SI

0.0 0.40 0.0 0.00 0.0 1.00
0.5 1.00 1.0 1.00 1.0 1.00
2.5 0.00 100.0 1.00 9.0 1.00

100.0 0.00 100.0 1.00

Windows		DOS	Difference	% difference	Brown
Cell bed elevation	91.65	91.65	0	0.00	Trout –
Water surface elevation	92.456	92.47	0.014	0.02	Fry
Depth	0.806	0.82	0.014	1.71	HSC ID
Depth Suitability Index	0.0708	0.096	0.025	26.25	
Combined Suitability Index	0.0644	0.087	0.023	26.25	
Weighted Usable Area	8.698	11.79	3.096	26.25	

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

Conventions Used in this Document

Chapter 1, Introduction to the Physical Habitat Simulation System

1

Objectives

Associated Laboratory Exercises

Number: 100102

Enter these HSC in the SAMPLE data set using **\File\New Curve** in the **Suitability Curves** Window. Examine the newly created HSC sets using the **Graph** feature. When finished, go back to the main menu and save the project.

The HSC in this project can now be used in other projects by importing the HSC data. In the **\Edit\Suitability Curves** window the ability to import from an existing project is found under **\File\Import\From Existing Project**. One may also import FISHCRV format text files prepared in DOS PHABSIM version 2 format using the **Import From Text File** menu item. You will be prompted to select which curves to import.

Thus, it is possible to create a project with the sole purpose of containing a library of HSC curves and import the desired HSC for each specific study from this library as needed. Try creating a new project and importing the HSC from this revised Lab7 project. Give the new project the name “New Curves”. The “New Curves” project could become a library of curves by importing or building successive HSC data sets as described above. Note that any individual curve can be selected from the source project and placed in the receiving project as long as the curve ID numbers are unique.

Laboratory 8. AVDEPTH and AVPERM Models

Objective

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

PREFACE

The objective of this laboratory is to introduce the user to the hydraulic parameter based model AVDEPTH/AVPERM. This concatenated name is retained for familiarity with past versions of the PHABSIM system. The laboratory will demonstrate the use of this model as well as illustrating the type of model outputs

The AVDEPTH \AVPERM model characterizes a study site channel in terms of hydraulic properties at each cross section. The AVDEPTH/AVPERM model can be used to characterize a stream in terms of a qualified wetted perimeter at each simulated discharge. The wetted perimeter can be reported for areas at least as deep as up to five user-specified depths. The output is provided for each cross section as well as for reach-aggregated results. In addition, the program produces summary output of average channel velocity, hydraulic depth, hydraulic radius, wetted width, wetted perimeter, Froude number, wading parameter, drag parameter, and cross sectional area. The wading parameter is calculated as the product of the depth times the velocity and can be used as an index of safe wading conditions at a cross section. The drag parameter is computed as the velocity squared times the depth.

The AVDEPTH/AVPERM model requires that the simulated hydraulic properties for use within the model have been generated by one of the hydraulic models (i.e., STGQ, MANSQ, or WSP). At least one of those models must have been run prior to use of AVDEPTH/AVPERM.

Simulate the Hydraulic Properties within the River

Ensure that the SAMPLE2.phb project file is available in the current working directory before starting the laboratory. At this point, STGQ, WSP, and VELSIM have been run in previous labs so the needed depth and velocity information is contained in the project database.

Run the Model and Examine the Output

Move to \Models\AVDEPTH\AVPERM and note the table for input of depth increments to be used in AVDEPTH/AVPERM. For this exercise, the five depth increments of 0.5, 1.0, 1.5, 2.0, and 2.5 ft. will be used. If the user does not supply any depths, the program computes the summary parameters based on all available depths at a cross section. Results are viewed in the **Average Parameters** and **Depth Parameters** tabs. Scroll these tables to see all entries. As with all PHABSIM for Windows output tables, these can be copied by dragging the mouse from the upper left to lower right corner, right clicking, and selecting copy from the pop-up menu. Figure L8-1 provides a partial Average Parameter and Depth Parameter table listing. Average parameters for the entire reach are available in text output only; click the **Text File** button to obtain this output. Figure L8-2 shows a reach level summary table produced by AVDEPTH/AVPERM.

Figure L8-1. Partial average parameter and depth parameter tables from AVDEPTH/AVPERM.

[illegible]

Figure L8-2. Whole study site average parameter table from AVDEPTH/AVPERM.

The summary table in Figure L8-1 shows the stream width at each of the simulated discharges at cross section 0.0, followed by the total width of the stream (i.e., the SUM column) with a depth greater than 1.0, as well as the maximum contiguous width with depths greater than 1.0. These summaries are repeated for each of the depths specified by the user in the **AVDEPTH/AVPERM input** tab. Use the scroll bars to view all of the output in the **Average Parameters** and **Depth Parameters** tables.

The final output summary at the bottom of the file (see Figure L8-2) contains this same information for depths aggregated over the entire study reach. The user should note that the AVDEPTH/AVPERM model computes the reach-aggregated results using the cross section weighting factors assigned in **Edit\Cross Sections**. Therefore, changing the weighting given to particular cross sections will change the summary results displayed in this table.

Laboratory 9. The HABTAE Model

Objective

The objective of this laboratory is to introduce the HABTAE model for calculating available habitat quantity and quality. The lab will explore several commonly used modeling options as well as demonstrate the sensitivity of habitat model predictions to different approaches taken in the hydraulic modeling phase of PHABSIM.

Programs Used: HABTAE

Data Files Used: Lab9.phb

Introduction

The HABTAE program allows integration of biological requirements of target species and life stages, represented in the form of Habitat Suitability Criteria (HSC), with hydraulic simulation results. This integration generates a number of indices of available habitat quantity and quality. These include weighted usable area, bed area, and volume. These results can be computed for each cross section, as well as for aggregated summaries at the study site level. A description of the calculations used in the HABTAE program can be found in Chapter 4 of the manual.

In this lab, we assume that water surface profile modeling has been finished and quality controlled so the VELSIM program will be used for all hydraulic simulations. However, several different modeling approaches for simulation of velocities will be explored to examine the impact on calculated available habitat. The lab is divided into several steps, which address a specific computational aspect or evaluation of HABTAE model sensitivity to different modeling options. The principal sections of the lab are:

- a. Aggregation Method for Computing Combined Suitability
- b. Computing Habitat for Cross Sections versus Reaches
- c. Calculation of Habitat Quality
- d. Effects of Velocity Simulations on weighted usable area (WUA) Results

The user is encouraged to examine the full range of computational capabilities for the HABTAE model contained in Chapter 4 of the manual and explore use of the options not covered in this lab manual. An effective way to determine whether a particular option has value to the user for a given problem is to run the HABTAE model with 'standard' or 'default' settings and then compare the computational detail listings in the output with other selected options. This is often the best way to determine how or what the program is actually calculating and whether or not a particular option is appropriate for the problem you are attempting to solve.

Compare Aggregation Methods for Computing Combined Suitability

In this section of the lab, three computational methods by which the HABTAE program combines individual suitability for depth, velocity, and channel index within a cell to derive WUA will be examined. The three approaches include multiplicative, geometric mean, and limiting value methods (see manual Chapter 4). Make sure that the requisite data files listed above have been copied to the current working directory prior to beginning the laboratory. The following steps proceed in the general order of a habitat analysis.

Step 1. Generate Hydraulic Characteristics for Selected Stream Flows using VELSIM

The Lab9.phb project contains the results of simulating water surface profile and velocity distributions for the sample study site. You may want to compare the results you obtained at the end of the previous laboratory with these results.

To determine if the Lab9 project is ready for this next step, go to **\Reports\Graphs** and view the longitudinal profile for all discharges. Then view the velocity distribution for the simulated and observed discharges at each cross section. When you have determined that these are the correct profiles, you can assume the project now contains the necessary hydraulic and channel geometry property information needed to proceed with this laboratory.

Step 2. Select Species and Life Stages

Prior to setting the HABTAE options, the target species and life stages to be used in the analysis must be determined. Specifically, HSC identification numbers must be selected or input to PHABSIM. Go to **\Edit\Suitability Curves>Select\By ID** to view a list of all of the HSC curve sets that have been loaded into the project thus far. Locate the HSC ID numbers for Bull Trout fry, juvenile, adult, and spawning life stages (i.e., 100101, 100102, 100103, and 100104). If Bull Trout HSC has not been loaded, you may load them now by importing them from an old PHABSIM format FISHCRV file. You will find FISHCRV.LAB in the working directory.

Step 3. Set the HABTAE Options

Next go to the HABTAE computational options tab at **\Models\Habtae\Computations**. Note that **Habitat Calculations** (old IOC Option 9) has been set to **Standard Calculation** so multiplicative combination of depth, velocity, and channel index HSC values for each computational cell will be the form of the WUA calculation. This option will be changed in subsequent HABTAE model runs as part of the laboratory to examine effects of different suitability aggregation techniques on WUA predictions. Note that WUA Calculations are set to **Calculate WUA for Reach**. Also note that **Use Zero CI in calculations** (IOC 18) has been selected so that a channel index code of '0' will match the associated HSC curve coordinate data of '0' for channel index.

Next go to the **\Models\Habtae\Limits** tab and select **No restrictions on velocities** to allow the HABTAE program to run if it encounters negative velocities or velocities that are greater than 15 feet/second.

Finish setting options by going to the **..\Life Stages** tab and clicking on each HSC curve set ID number you wish to use in the habitat simulation. Select the 4 life stages of Bull Trout (i.e., 100101, 100102, 100103, and 100104) by clicking on each of them to highlight the Bull Trout entries.

Step 4. Run the HABTAE Program and Examine Output

Click the **Run** button in the **..\Output Options** tab to run HABTAE. Move to the **..\Results** tab where you will find tabular values indicating the combined suitability for each cell. Select the **Discharge** and **Result** you want to view and the table will update automatically. You may view a color graph of the habitat suitability distributed over the study site for the selected result by clicking on **Graph**.

Next move to the **..\ZHAQF Results** tab to review tabulated WUA values calculated for the study site. As in the velocity and WSL sections, the results may be viewed by clicking on the **Graph** button. The relative differences in magnitude and shape of the WUA versus discharge curves for these life stages are a result of the habitat calculated from the HSC curves in response to the hydraulic properties at each discharge. The program also writes to a numbered ZOUT file as illustrated in Figure L9-1.

These summary tables are aggregated totals for all cross sections. This information is repeated for each life stage in the numbered ZOUT file produced by running HABTAE. To view this table, check the filename.history file for the number of the ZOUT file produced by the last HABTAE run and open the ZOUT with a text editor.

To easily view the ZOUTxx file, move to Windows Explorer and the working directory for your study. Then drag and drop the latest ZOUTxx file on to the Wordpad icon on the desktop. Highlight all text in the file and set the font size to 8 pt for ease of viewing the text without scrolling the lines.

The tabular listing in the **..\Zhaqf Results** tab contains a tabular summary of total WUA for each species and life stage at each discharge. Clicking the check box marked **Include total area** will add a column for total surface area at each discharge. A list box for **Species** is provided so analysis results for different species can be displayed sequentially. Note that all life stages for Bull Trout are given in one table due to the format of HSC curve numbers used in the FISHCRV.LAB data file (i.e., 100101, 100102, 100103, etc.). If these HSC curve numbers had been 100001, 200001, 300001, 400001, then output for each life stage would have been displayed as a separate species.

As would be expected from the differences in HSC curves for different life stages, the WUA versus discharge plot found using the **..\Zhaqf Results\Graphs** button shows that adults have the most habitat overall, and that as flows increase, fry and juvenile habitat availability tends to decrease (See Figure L9-2). This should make intuitive sense because velocities are increasing within the main channel areas, which makes these areas increasingly unsuitable for life stages with less swimming ability. Once this plot has been examined, return to the **..\Zhaqf Results** and click **Print** to produce a copy (or copy and paste the table to a spreadsheet) of your Bull Trout results using multiplicative combination of HSC criteria. Label this copy "Standard Multiplicative WUA Results".

Windows		DOS	Difference	% difference	Figure L9-1.
Cell bed elevation	91.65	91.65	0	0.00	
Water surface elevation	92.456	92.47	0.014	0.02	
Depth	0.806	0.82	0.014	1.71	
Depth Suitability Index	0.0708	0.096	0.025	26.25	
Combined Suitability Index	0.0644	0.087	0.023	26.25	
Weighted Usable Area	8.698	11.79	3.096	26.25	

Acknowledgements

i

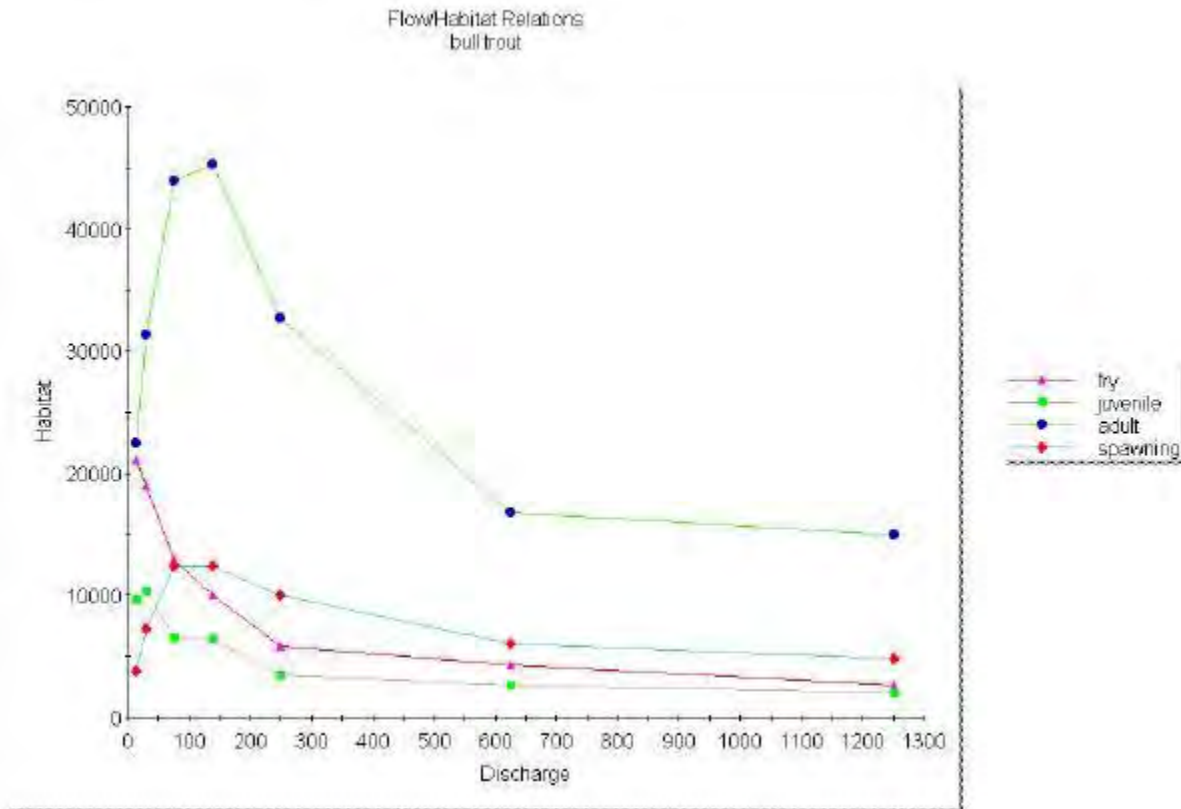
PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Aggregate habitat results for Bull Trout fry life stage at each of the simulated discharges. **Figure L9-2.** Multiplicative WUA values for Bull Trout.



Step 5. Compare the Effect of Various Combined Suitability Values on Habitat Predictions

Changing the manner in which the HABTAE program computes combined suitability for each computational cell has the potential to change resulting predictions of WUA. In previous habitat simulations, WUA was computed using the multiplicative approach. In this step, the HABTAE program will use the geometric mean.

Go to the **\Models\Habtae\Computations** tab and click **Geometric Mean**; then move to the **..\Output Options** tab and click **Run**. The results of this simulation are shown in Figure L9-3.

Comparing Figures L9-2 and L9-3 clearly demonstrates that the magnitude of WUA predictions change but in general the shape of the functional relationship in the WUA curves has remained essentially the same using both simulation options. The increased magnitude of WUA predictions should make sense since the geometric mean “compensates” for a single low suitability factor in a computational cell if the remaining two suitability factors are high. This should increase WUA values overall.

Finally, go to the **..\Computations** tab and click **Lowest Limiting Factor**; and again click **Run** in the **..\Output Options** tab. The results of this simulation are shown in Figure L9-4.

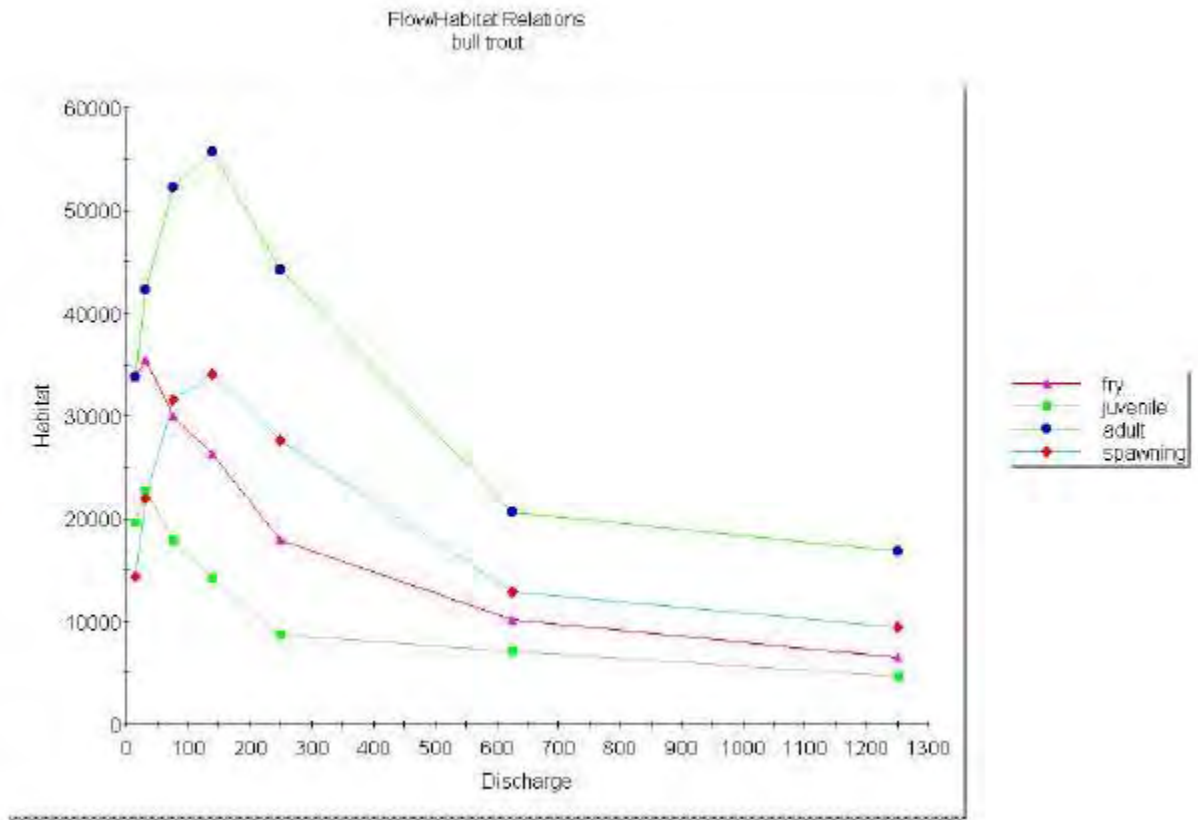


Figure L9-3. Geometric mean WUA values for Bull Trout.

A comparison of all three simulation results illustrates several interesting patterns. The geometric mean always produces more habitat than either the multiplicative or limiting factor method as would be expected. The limiting factor approach is always greater than the multiplicative method. These differences are an interplay between estimated hydraulic properties from hydraulic modeling and the functional form of species and life stage HSC curves.

The user should carefully consider which option or combination of options to use when estimating habitat. Each of the computational approaches tells the user something different that, when interpreted in the context of the biology of the target species and life stages, may help in the evaluation of flow regimes.

Computing Habitat for Cross Sections versus Reaches

The HABTAE program can be used to calculate WUA, weighted usable volume, or weighted usable bed area either for an entire reach or individual cross sections. This is accomplished by selecting the appropriate item for **WUA Calculations** in the **Computations** tab. In the next step of the laboratory, the HABTAE program will be used to produce results for each cross section. The analysis of habitat at particular cross sections can identify not only the amount contributed to total WUA by each habitat area but can also be used to focus your study on specific critical habitats.

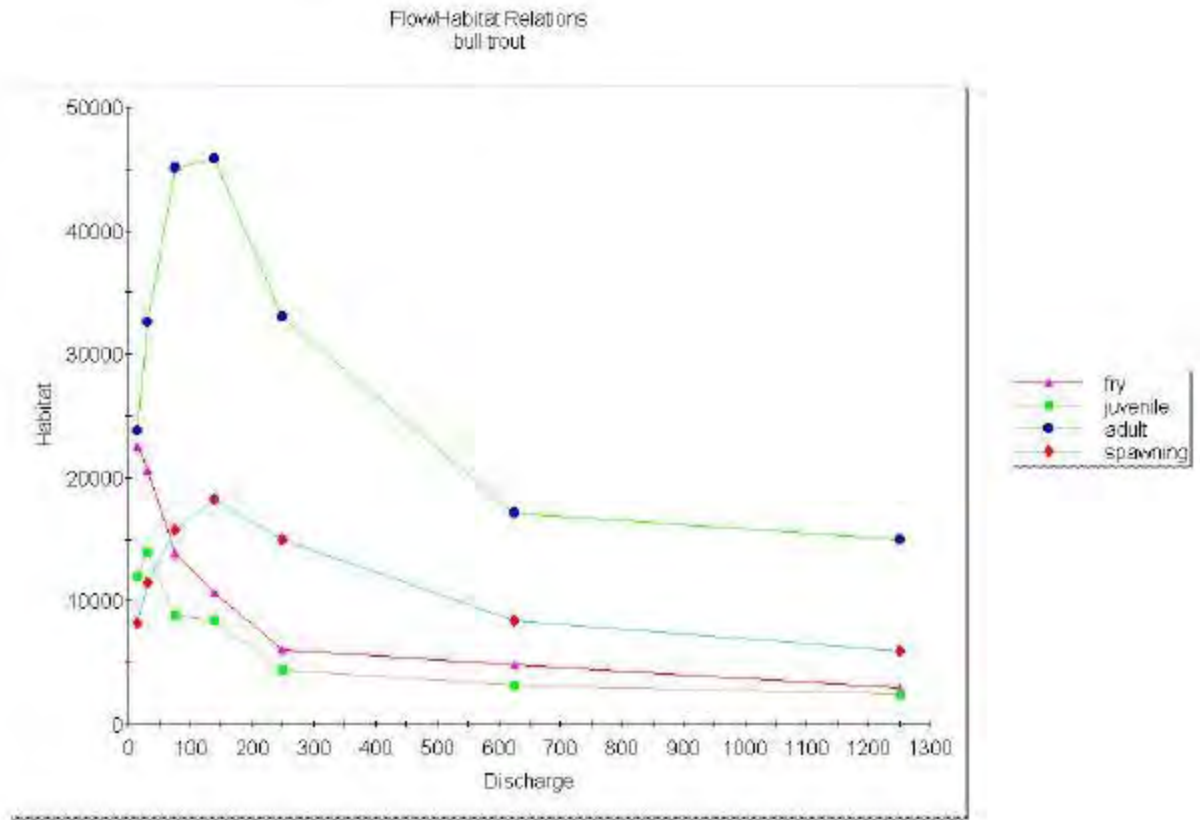


Figure L9-4. Lowest limiting factor WUA for Bull Trout.

Step 6. Change Habitat Options to Produce Cross Section Output

In the **..Computations** tab, set **WUA Calculations** to **Calculate WUA for Independent XSEC** and set **Habitat Calculations** to **Standard Calculation**. Then click **Run** in the **..Output Options** tab.

Using this option in HABTAE will generate summary tables for each species and life stage for each cross section. These tables are only contained in the ZOUT file created after running this HABTAE option. View the latest numbered ZOUTxx file using Wordpad and scroll down through the output to examine these results. When finished, exit Wordpad and return to the HABTAE program in PHABSIM for Windows. In the output (see Figure L9-5), you will find terms for weighted width and percent WUA. These terms are provided because each cross section is treated independently and therefore, there is no longitudinal direction over which to compute area of the computational cells.

This option in HABTAE is particularly useful for understanding how predicted habitat changes for a given species and life stage within specific types of mesoscale habitats. This may be important when considering impacts of alternative flow regimes on spawning habitat in riffles or over wintering habitats in pools, for example.

SPECIES -bull trout

LIFE STAGE -fry UNITS: TRADITIONAL VELOCITY TERM - MEAN

CFMIN = 0.00

CROSS SECTION 0.000000

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25

Figure L9-5. Excerpt of habitat results for individual cross sections.

Evaluation of Habitat Quality

All HABTAE program runs to this point in the laboratory have estimated total WUA. For a given discharge the program may indicate that of a total stream surface area of 100 ft² that there are 10 ft² of WUA. WUA could be composed of a single 10 ft² area with a combined suitability of 1.0 with the remaining 90 ft² of habitat having a combined suitability of 0.0. Alternatively, all 100 ft² of stream may have a combined suitability of 0.1. In both cases, total WUA would be 10 ft². In this section of the lab, the HABTAE program will be used to set a threshold on the magnitude of combined suitability to compute the amount of “high quality” habitat at each discharge.

Step 7. Calculate Habitat With Minimum Combined Suitability Factors

Go to the **..Limits** tab and click **Specify minimum factor by life stage** in the **Minimum Effective Composite Suitability Factor (IOC 19)** box. Then move to the **..Velocity Replacement Options** tab and enter the minimum composite suitability factor value you will accept in the CFMIN column for each life stage HSC number shown. For this laboratory, use 0.75 for all life stages. Then click **Run** in the **..Output Options** tab.

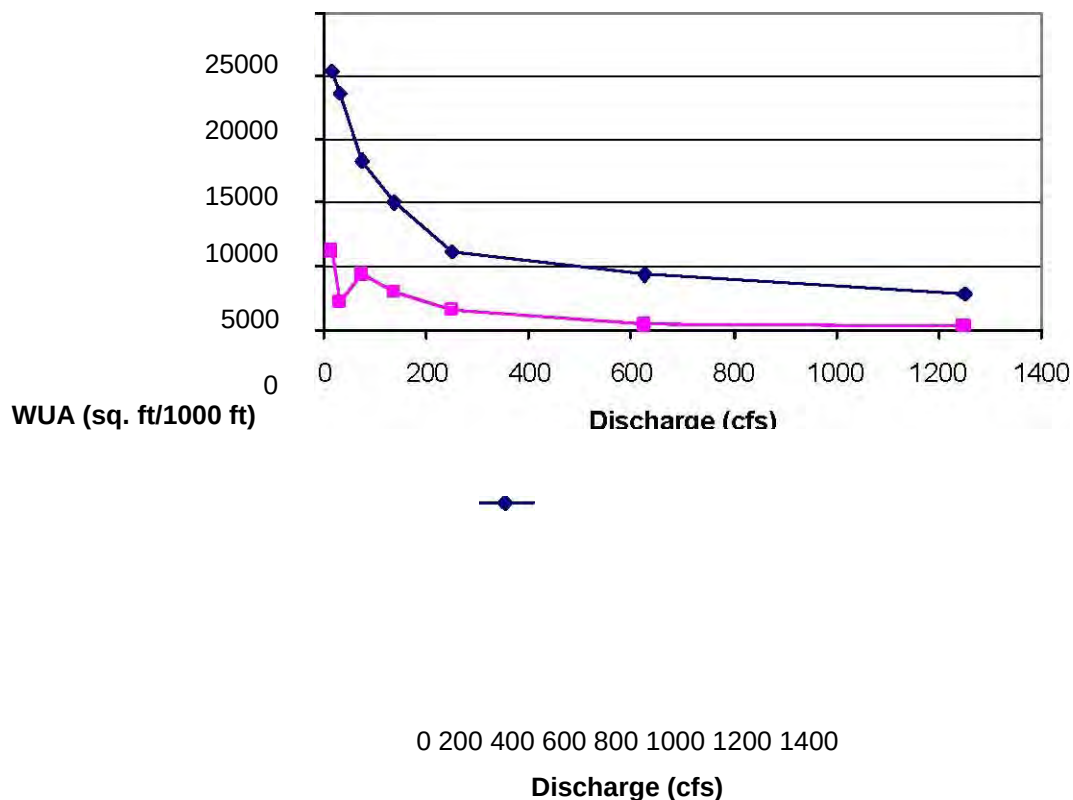
The results for total WUA and “high quality” habitat can be compared for each species and life stage. In the **..ZHAQF Results** tab, click the **Graph** button, select Bull Trout Fry and click the **Refresh** button. Figure L9-6 displays the results for Bull Trout fry where the line labeled No Limit is total WUA and the line labeled CF Limit = 0.75 is WUA with a combined suitability greater than 0.75. Making two runs of HABTAE with and without composite suitability factor limits and copying the results to a spreadsheet produced this figure. The Bull Trout Fry graph in PHABSIM for Windows should look like the CF Limit = 0.75 line in Figure L9-6.

Note the apparent decline in WUA at 30.2 cfs (the second discharge) compared to 15.0 and 75.2 cfs. By clicking the Graph button in **..Habitat Results** you can view a plot of composite suitability for all cells in the study site. The color key allows visual evaluation of which cells have more than 0.75 combined suitability. At 30.2 cfs, only cross section 201 has a significant amount of Bull Trout fry habitat. Whereas at either 15.0 or 75.2 cfs, at least one other cross section has relatively large amounts of fry habitat with a combined suitability of 0.75 or greater. At these low flows, large relative changes in habitat may occur with changes in flow as highly suitable areas become wetted and those same areas develop high velocities at greater flows.

Display the results for the remaining life stages of Bull Trout in both the **..Habitat Results** and **..ZHAQF**

Results tabs. Note that for this particular data set, high quality habitat is contributing to less than half of the total WUA over all ranges of discharge for all life stages. However, this is not always the case. In some instances, the amount of high quality habitat may make up only a small proportion of total available habitat over certain ranges of flows while dominating total available habitat at others. It is also not uncommon that the discharge at which high quality habitat is maximized may be different than the discharge at which total habitat is maximized. This type of analysis with HABTAE permits evaluation of tradeoffs between flows that may sacrifice total habitat to maximize high quality habitat at an alternative discharge.

Bull Trout Fry Habitat



No Limit

CF Limit=0.75

Figure L9-6. Bull Trout fry habitat with and without composite suitability limits.

Evaluate the Effects of Velocity Simulations on WUA Results

To illustrate the effects of hydraulic simulations on computation of available habitat, this part of the laboratory will use four different calibration/simulation velocity data sets as input to HABTAE for the production of WUA. Setting a total of four different velocity simulation options and generating WUA for each of the resulting velocity distributions will accomplish this. We will simulate velocities using the high flow velocity calibration data set, the medium flow velocity calibration data set, the low flow velocity calibration data set, and the discharge range distributed set as templates. We

currently have modeled velocities using the low flow velocity set as the template from 15 –75.2 cfs, the mid-flow velocity set for 139 cfs, and the high flow velocity set for 250 cfs and up. So we will begin there.

Step 8. Select different CAL sets within the VELSIM Program and Compute WUA with HABTAE for each

Velocity Template

Set HABTAE to produce standard WUA for the entire study site by setting **No limiting factor specified** on the **LIMITS** tab and **Calculate WUA for Reach** and **Standard Calculation** on the **Computations** tab. Click **Run**, go to **Zhaqf Results**, and **Print** the table. Alternatively, you may copy the table into a spreadsheet. (Do not forget to enter the column and row headings.) Label the printed copy or spreadsheet block, “Combined Velocity Templates”. Save the project using **\File\Save Project** before proceeding. We will come back to this project in the next lab so it is important to save the file now.

Next, go to **\Models\Velocity Simulation\Velocity Calibration Set Assignments** and set all combinations of discharge and cross section to 1. This will assign the low velocity set as the template for all velocity simulations. Click **Run** followed by **OK** to exit the velocity simulation window. Save this project under a new name using **\File\Save As**. Give the project the name “Lowvel” and ensure it is located in a directory subordinate to the working directory “Lab9”.

In **\Models\HABTAE**, click **Run** (you have already set all the options). Go to the **Zhaqf Results** tab and print the table of WUA values. Label this copy or spreadsheet block “Low Velocity Template”.

Repeat this process by setting all combinations of discharge and cross section to velocity calibration set 2 and then 3 with appropriate labels for middle and high velocity calibration set on the printed (or copied and pasted) tables of weighted usable area. Save the projects under new names using **\File\Save As**. Name the projects “Midvel” and “Highvel”, and ensure they are located in directories subordinate to the working directory “Lab9”. You should now have four sets of habitat results and four projects located in separate directories.

Examining the four sets of results for Bull Trout juveniles shown in Figure L9-7 shows convincing evidence that the choice of velocity calibration data set can impact the relationship between WUA and discharge over at least part of the flow range. Results for different species and life stage HSC relationships and different hydraulic calibration data can produce similar or widely differing results. The user needs to carefully consider her (his) choice of calibration data sets, HSC, and modeling options when applying PHABSIM. It is up to the investigator to justify the choice of options and data used in the context of the particular instream flow assessment. Usually these choices are made based on goodness-of-fit, reasonableness, and study objectives.

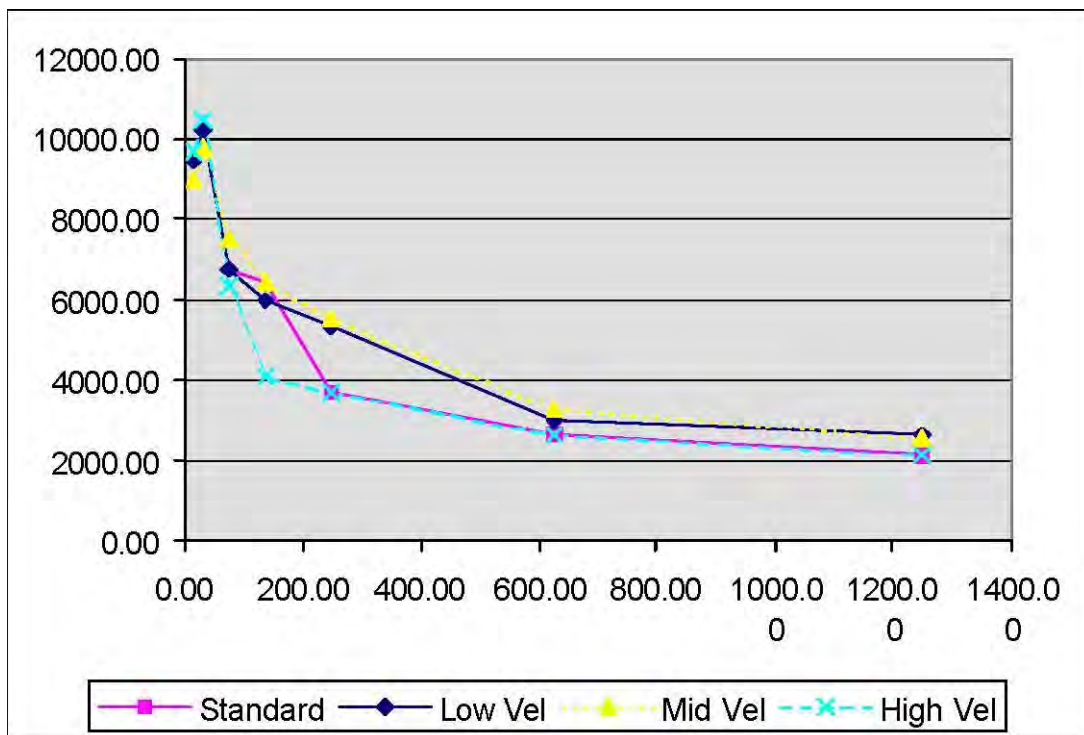


Figure L9-7. Bull Trout juvenile habitat produced by four different velocity set templates.

Laboratory 10. Conditional (Adjacent) Velocity Habitat Simulations Objective

The objective of this laboratory is to introduce calculation of habitat based on adjacent or “conditional” velocities using the HABTAE model.

Programs Used: HABTAE, Excel

Data Files Used: Lab10.phb, highvel.phb, midvel.phb, lowvel.phb, adjvelhab.xls

Introduction

In addition to “standard” Weighted Usable Area calculations, the HABTAE program allows the user to generate available habitat where adjacent velocity conditions are combined with the habitat suitability criteria to determine habitat worth.

In this lab, the VELSIM program will be used for all velocity distribution simulations using four different velocity simulations to explore the impact on calculation of available habitat within HABTAE. To facilitate presentation of the material, the lab has been broken into several sections, which address a specific computational aspect or evaluation of model sensitivity with HABTAE. The principal activities of the lab are:

- Creation and Modification of HABTAE Options Control Files for Simulations
- Conditional Velocity Simulations
- Generation of Hydraulic Properties using Different Velocity Simulation Approaches
- Conditional Velocity Simulations with Different Velocity Modeling Approaches

The user is encouraged to examine the complete listing of computational capabilities for the HABTAE model contained in Chapter 5 of the manual and explore use of computational options not covered in this lab exercise. The best way to determine whether a particular option has value to the user for a given problem is to run the HABTAE model with 'standard' or 'default' settings and then compare computational detail listings in the output with other selected options. The laboratory is presented in 7 steps that lead you through the conditional velocity analysis process.

Step 1. Run HABTAE with Standard Options

In the **..\Output Options** tab, set the following items:

- Click the **Write Computational Details** check box to cause computational details to be printed to the next numbered ZOUT file.
- Click the **Write WUA or WUV** radio button in the **ZHAQF Options** box to write WUA calculation results to the ZOUT file.
- ☐ Click the **Write Flow Data** check box so the ZOUT file will also contain the flow data used to generate these habitat results.
- In the **Computations** tab, set the following items:
 - Click the **Use Zero CI in Calculations** check box, as channel index values of zero should calculate as zero.
- Click the **Calculate WUA for Reach** radio button in the **WUA Calculations** box to produce aggregated weighted usable area as the final habitat result.
- Click the **Standard Calculation** radio button in the **Habitat Calculations** box to ensure that the “standard” multiplicative calculation of composite suitability is performed.

In the **Life Stages** tab scroll the table and click on each of the four life stages of Bull Trout. For this exercise, do not include any other species. Only the four Bull Trout lines should be highlighted. Make a note of the HSC numbers for each life stage as you will use them later.

Return to the **\Models\Velocity Simulation\Velocity Set Assignments** window and check that Cal Set 3 has been assigned to all discharges at all cross sections. If this has not been done, do it now and rerun the velocity simulation.

These settings prepare the HABTAE model to perform the standard habitat calculation for four life stages of Bull Trout. In the **..Output Options** tab, click the **Run** button. Move to the **ZHAQF Results** tab. On the Windows Desktop, start Microsoft Excel (or your preferred spreadsheet package) and open the file `adjvelhab.xls`. Drag the mouse from the upper left to the lower right corner of the ZHAQF Results table, right click, and select **Copy**. Move to Excel and paste to the first block of values starting at cell A9. This places the “standard” habitat calculation results in the spreadsheet.

Step 2. Select HABTAE Options for a Minimum Adjacent Velocity Limit Calculation

In the **Adjacent Velocity** tab, set the following items:

- In the **Use VLIM as** box, click the **Minimum** radio button to search for a velocity that is greater than or equal to the velocity you will define below as VLIM. That is, VLIM is set to act as a lower (minimum) bound.
- In the **WUA Calculation when VLIM not found** box, click **WUA = 0** to cause no WUA to be calculated in the current computational cell if the user-defined minimum velocity is not found within a user specified distance.

Enter scan distances and threshold velocities to be used for each species and life stage in the **Dist** and **VLIM** columns of the table in the **Scan distance, velocity limit, and initial velocity** box. These values are entered next to the appropriate HSC curve ID numbers for Bull Trout; 100101 for fry; 100102 for adult; 100103 for juvenile; and 100104 for spawning. (Scroll the table using the scroll bar until the needed HSC curve numbers are displayed.)

For the purposes of this lab exercise, enter a restrictive scan distance (Dist) for fry (5 feet), a larger distance for juveniles and adults (10 feet), and zero distance for the spawning life stage to simulate immobility of incubating eggs in the analysis. It is incumbent on the investigator to determine an appropriate distance to scan for particular species and life stages when using the adjacent velocity calculations in the HABTAE program.

Similarly, enter a different threshold velocity (VLIM) value for fry (0.5 fps) and adults (1.0 fps), and the same value for juvenile and spawning (1.5 fps). The choice of limiting velocity is again a matter of professional judgement. Examining the HSC curves for velocity can often provide insight as well as searching published literature on sustained swimming speeds or related life history information. The values chosen in this laboratory are for illustrative purposes only.

In the **Velocity Replacement Options** tab, leave all values set to zero as only mean column velocity is being considered and no nose velocity issues are being explored at this point. It is possible, however, to base adjacent velocity calculations on nose velocities as long as you have habitat suitability criteria that reflect nose velocity, search distance and velocity limit information that is appropriate to such a calculation. Little research has been done in this area so such information may be scarce.

This sets up the Adjacent Velocity as Minimum Limit calculation for four life stages of Bull Trout. In the **Output Options** tab, click the **Run** button. Move to the **ZHAQF Results** tab. On the Windows desktop, start Microsoft Excel (or your preferred spreadsheet package) and open the file adjvelhab.xls. Drag the mouse from the upper left to lower right corners of the ZHAQF Results table, right click, and select **Copy**. Move to Excel and paste to the first block of values starting at cell A21. This places the “VLIM is Minimum” habitat calculation results in the spreadsheet.

Step 3. Run HABTAE With a Maximum Adjacent Velocity Limit

In the **Adjacent Velocity** tab set the following items:

- ☐ In the **Use VLIM as** box, click the **Maximum** radio button to search for velocity less than or equal to the velocity you will define below as VLIM. That is, VLIM is set to act as an upper (maximum) bound.

Leave all other options the same as in Step 2 above. Click the Run button as above and copy and paste the habitat results into the spreadsheet at cell A33. This places the “VLIM is Maximum” habitat calculation results in the spreadsheet.

Step 4. Compare Standard and Adjacent (Conditional) Velocity Simulations

This section of the laboratory will compare HABTAE habitat predictions based on both maximum and minimum threshold conditional velocity simulations. In the previous steps, results have been generated using the standard habitat calculation, conditional velocity simulation using a minimum threshold, and conditional velocity simulation using a maximum threshold. In each instance high flow calibration velocity simulation results from VELSIM were used.

To begin this evaluation, move to the **Habitat Results** tab. There you will find dialog boxes for Curve ID, Cross Section and Discharge. Clicking the triangular down arrow at the right of each box displays a menu of the options available for **Curve ID**. Select 100101 Bull Trout fry. For **Cross Section**, select 0.000, and for **Discharge** select 139.0 cfs. The table now displays the velocity suitability index value (VEL SI), the Depth SI, the channel index suitability value (Sub SI), the adjacent velocity suitability factor (Ad Vel), the combined suitability factor for each cell (Factor), the cell area and the cell weighted usable area (WUA). A separate table of results will be displayed for each combination of Curve ID, Cross Section, and Discharge selected as shown in Figure L10-1.

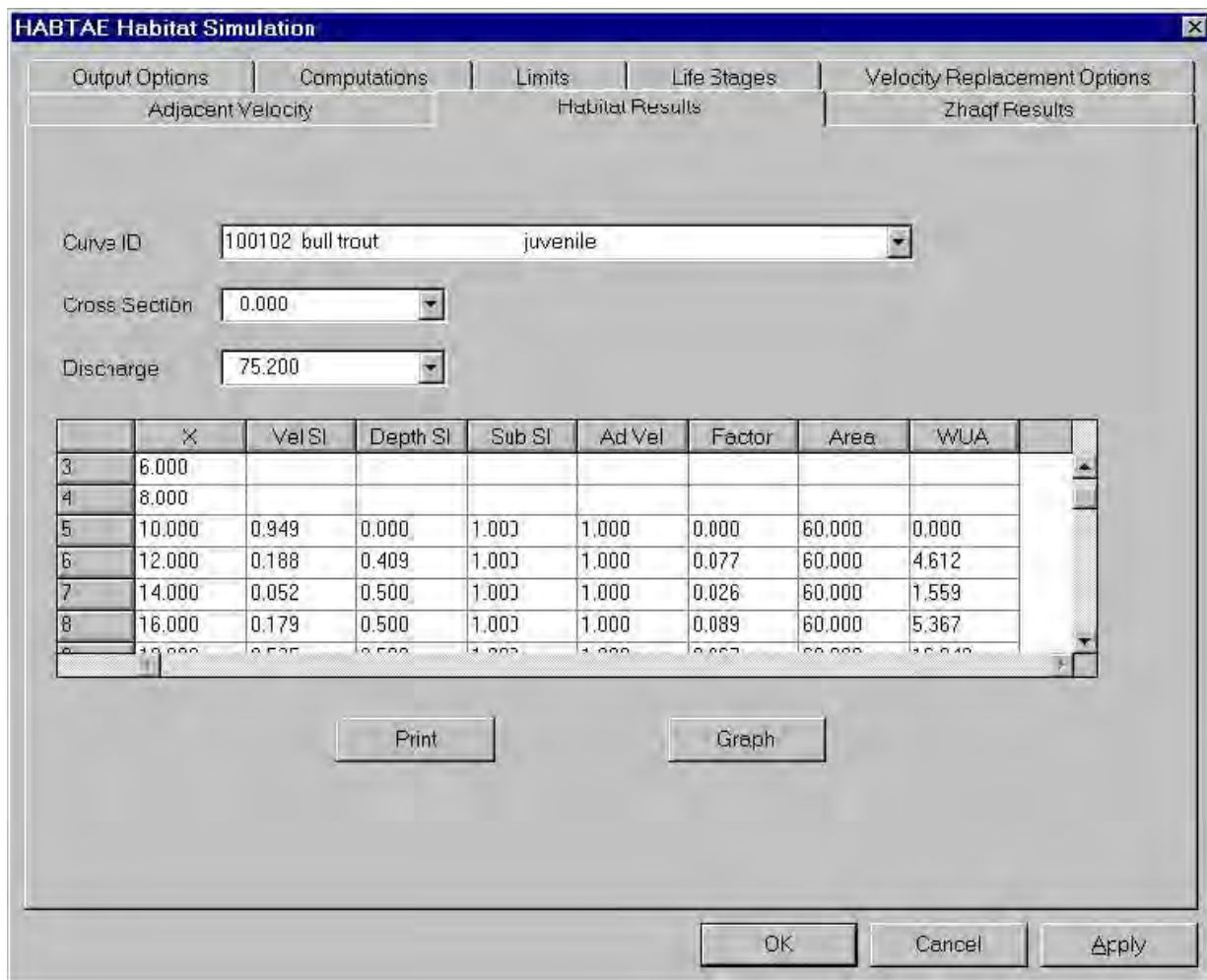


Figure L10-1. Habitat results table.

This table may be copied by dragging the mouse from the upper left to lower right corner, right clicking and selecting copy in the menu provided. The table may then be pasted to a spreadsheet or report as needed. Table headings are not included in the copy operation, so it is often useful to prepare a spreadsheet containing the headings as a template to receive this information.

The habitat results may be graphically viewed by clicking the **Graph** button. Both plan view and 3-D rotatable graphics are provided. The graphical display gives an indication of where on each transect the most suitable conditions exist. At the top of the graph window, dialog boxes similar to the **Habitat Results** tab allow the user to select which **Curve ID** and **Discharge** are to be viewed. Click **Refresh** to update the plot when each menu change is made.

Note the areas of high quality Bull Trout fry habitat at 139 cfs. Red is used for the highest value range. You can see that the highest composite suitability is less than 1.0. Why is this?

Now select 15 cfs and click **Refresh**. What differences do you see between this view and the 139 cfs view? Reduce the size of this graph window by dragging a corner so you can see the HABTAE window, but leave the graph window open for later use.

In the HABTAE Habitat Simulation window, go to the ZHAQF Results tab and click the graph button. In the Species dialog box select Bull Trout fry. Note the shape of the habitat-discharge relationship. Resize both this and the Habitat Results graph window so both can be viewed on screen at the same time. (On smaller monitors, it may be necessary to overlap the two graph windows and alternately click them to bring one or the other to the foreground or you may find it convenient to print the **ZHAQF** plot.)

While viewing the **ZHAQF** plot, select (and refresh) each discharge in the **Habitat Results** graph. How do the composite suitability values explain the resulting ZHAQF plot?

Note that at the lower discharges, the area of fry habitat occupies much of the stream bed. However, at the higher discharges, fry habitat is relegated to the stream margins. As the flow increases, the number of cross sections with suitable fry habitat at the stream edges decreases and the amount of area represented as high quality habitat (i.e., displays in red) decreases. Figures L10-2 to L10-4 illustrate the difference between the standard, minimum and maximum limit habitat for one discharge.

Note the loss of habitat at the fourth cross section (168 to 201 ft upstream) between the standard and “minimum” adjacent velocity calculations. This accounts for the lower conditioned habitat value at 15 cfs seen in the habitat flow relation displayed at the upper right. Also note that the fourth cross section has a large area of good habitat under the conditions of the “maximum” calculation. When the limiting velocity (VLIM) is treated as a lower bound (minimum) no cells are found within the search distance with velocities higher than VLIM at the fourth cross section. Thus, the final weighting factor is zero due to the adjacent velocity condition. In contrast, when VLIM is treated as an upper bound (maximum), there are ample cells with velocities lower than the limit and the habitat at the fourth cross section at 15 cfs is substantially the same as the standard calculation.

You can use the graphical display to determine the cause of the trend toward less fry habitat at higher discharges by selecting from the **Depth SI**, **Velocity SI**, and **Channel Index SI** radio buttons in the **Habitat Results** plot. If you select the Depth SI button and click refresh while displaying habitat results for 250 cfs, you will see a large area of the stream turn red. Thus, it is unlikely that Depth is the limiting factor. However, if you select Velocity SI, the plot shows minor changes from the composite suitability plot. Thus, it appears that velocity is the limiting factor that causes the fry suitability to decline with increasing discharge. This is true for the standard and both conditional velocity calculations. Why?

Now that we have considered how the habitat suitability for depth and velocity influences the shape of the habitat-discharge relation, we are ready to compare the three adjacent velocity limit approaches chosen earlier. Return to the [adjhabvel.xls](#) spreadsheet and note the graphs displayed to the right of the data entry area. (If you did not have time to complete this portion of the lab, a worked example is contained in Sheet 2 of the spreadsheet.)

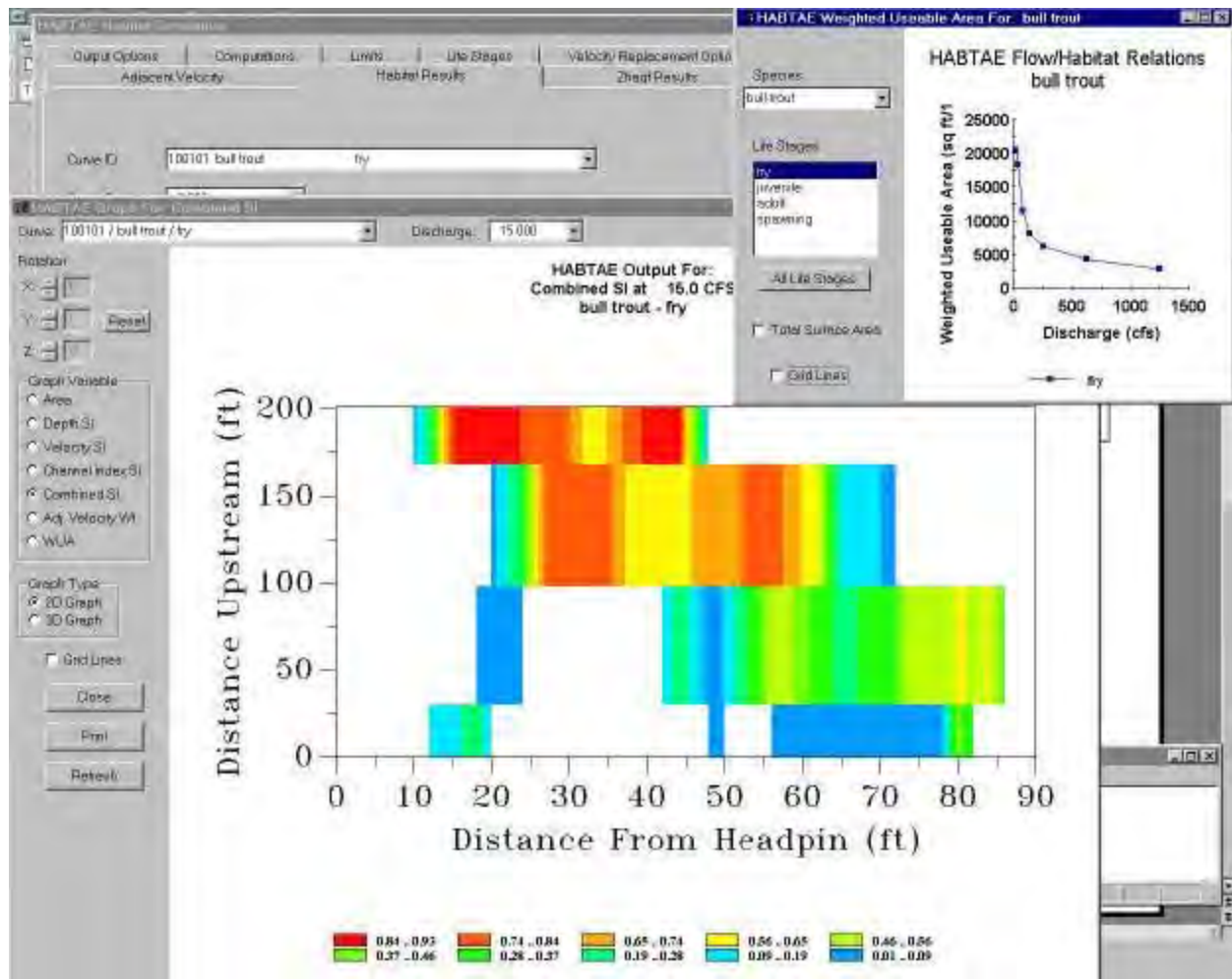
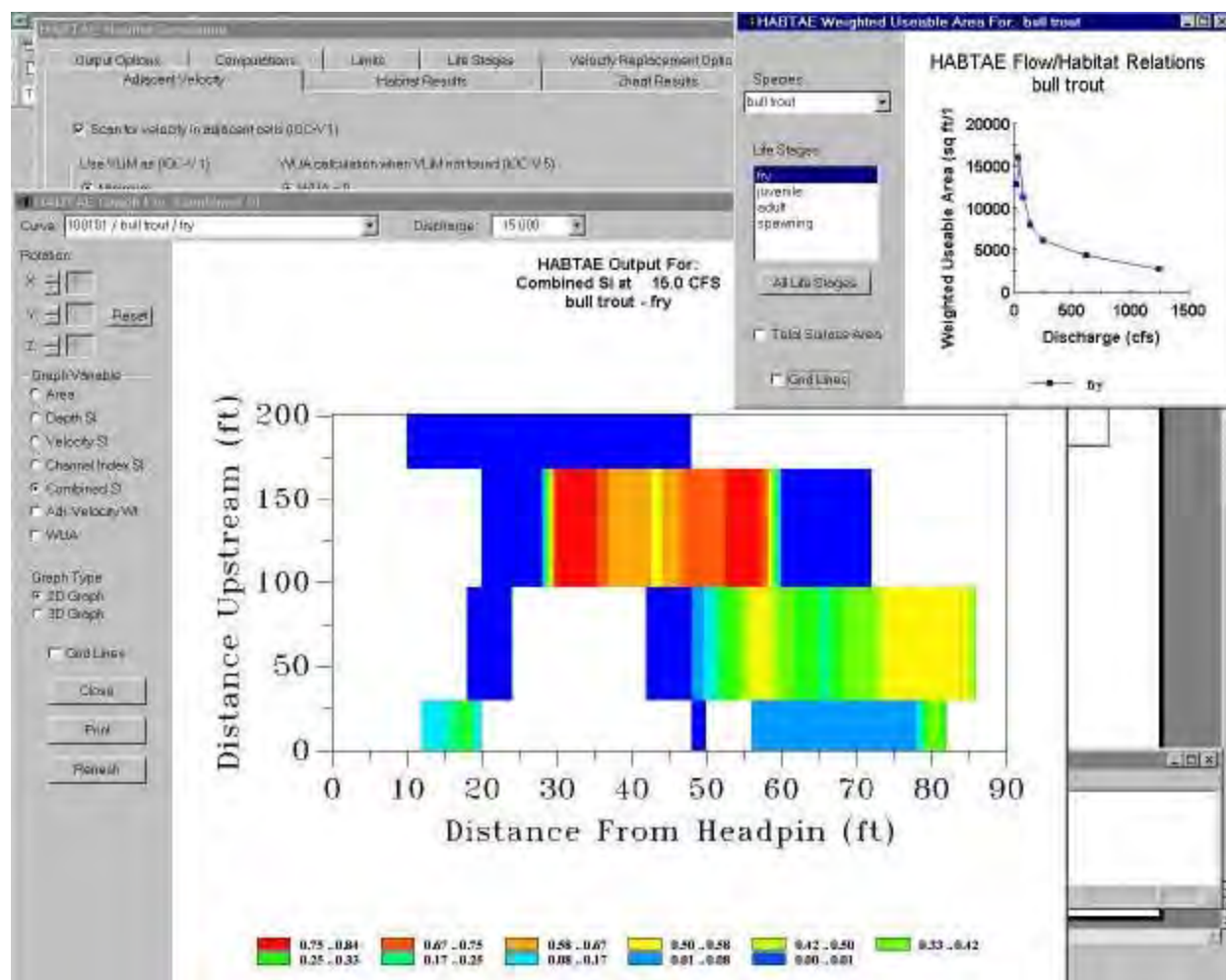
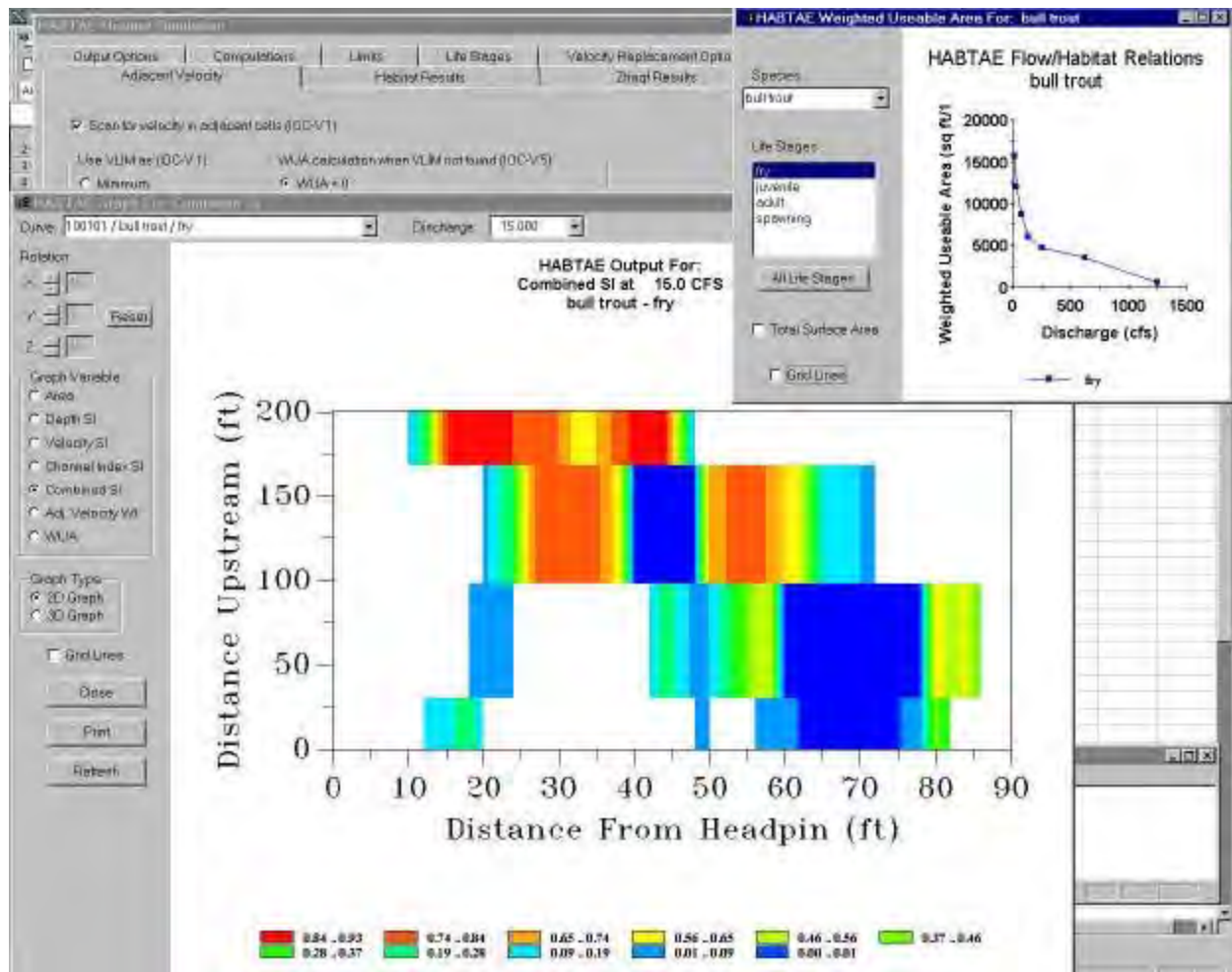


Figure L10-2. Bull trout fry habitat plan view, standard calculation. **Figure L10-3.** Bull trout fry habitat plan view, minimum **adjacent** velocity calculation. **Figure L10-4.** Bull trout fry habitat plan view, maximum adjacent velocity calculation.





These examples should demonstrate that for part of the flow range some life stages were not affected by use of conditional velocity simulations based on the criteria specified for either the maximum or minimum thresholds in conjunction with the user-specified scanning distances. The greatest impact on WUA across the entire range of discharges was obtained for the spawning life stage. Note that spawning was the only life stage where scan distance was set to >0'. The combination of threshold velocity and scan distances using the minimum threshold gave similar results to the standard velocity simulations for all life stages except spawning. This suggests that for most flows, HABTAE was able to find a velocity value above the threshold velocity within the specified scan distance for these life stages. This was not true at the very lowest discharges, but it is reasonable that fewer high velocity cells would be encountered at the very lowest flows.

Conversely, using the maximum threshold, there were more instances where HABTAE was not able to find a velocity that was less than the specified maximum (upper bound) within the scan distance for fry, adult, and spawning. Therefore WUA totals were reduced compared to the standard velocity simulations. Refer to the adjacent velocity calculation example in Chapter 4 of the manual if you have questions about the effect of these conditional velocity simulations. Again, the spawning life stage was most strongly affected due largely to the zero scan distance.

The degree to which conditional velocity simulations will affect WUA relationships will be a function of the form of the HSC curve for velocity, velocity limits specified, and the scanning distance supplied by the user. These factors will also result in either greater or lesser changes between target species and life stages. It is the responsibility of the investigator to justify his (her) choice of modeling options and, in particular, choice of velocity limits and scanning distances used for the species and life stages involved in each project analysis.

Step 5. Effects of Changing Threshold Velocities

To better illustrate the ideas discussed above, move to the **Adjacent Velocity** tab and change **VLIM** for Bull Trout juvenile and adult to 4.0 feet/second and select the **Minimum** radio button in the **Use VLIM as** box. From the comparison of simulation results in Step 4, relatively small differences between minimum and standard velocity simulations were obtained for juvenile and adult Bull Trout. To generate results for the higher VLIM, move to the **Output Options** tab and **Run** the simulation, then move to the **ZHAQF Results** tab and view the graph. Select Juvenile and Adult life stages only. You may also copy and paste the ZHAQF table into the adjvelhab.xls spreadsheet in the space identified as REVISED VLIM FOR JUVENILE AND ADULT, row 50.

By viewing the graphs to the right of the data table, it is apparent that setting the minimum threshold to a higher value has dramatically altered simulation results for both of these life stages. In fact, at lower discharges the results would indicate that velocities greater than 4.0 feet/second simply do not exist in the channel. Why? Confirm this is true by reviewing the velocity distribution plots for the lower discharges in either **\Models\Velocity Simulation\Results\Cross Section** or **\Reports\Graphs\Bed Profile with WSL/Velocities**. You should find there are no velocities greater than 4.0 fps until a discharge of 650 cfs is simulated.

The fact that WUA for Bull Trout juvenile (and adult) is 0.0 at discharges 250 cfs and below, means that HABTAE was unable to locate velocities greater than 4.0 feet/second within the given scan distance for each computational cell. Therefore set the computational cell WUA to zero (i.e. in **..\HabtAE\Adjacent Velocity** the **WUA = 0** button was selected in the **WUA calculation when VLIM not found** box.) At simulated discharges of 650 cfs and 1,250 cfs, hydraulic predictions are generating velocities in at least some computational cells that are greater than 4.0 feet/second and, therefore, a small amount of conditional WUA is predicted for these life stages.

Step 6. Generation of Hydraulic Properties using Different Velocity Simulation Approaches

You have already run the VELSIM program to produce the four velocity simulation alternatives that will be used in this lab. For convenience, you will find them in the Sample folder as noted in Table L10-1 below:

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	36.25

Table L10-1. Project names for different velocity simulation options.

To use any of these projects in PHABSIM for Windows, use **\File\Open Project** and move to the desired project directory using **Browse**. Once in that directory, the file *projectname.phb* will be visible in the Open File dialog box. Double click the project file to open the project.

In previous laboratory steps, effects of different conditional velocity simulation approaches were examined to

LABORATORY 10 – CONDITIONAL VELOCITY HABITAT
SIMULATIONS

compare the HABTAE habitat predictions using these options. In this step, the effect of different hydraulic simulation approaches on conditional velocity simulations using a minimum threshold approach will be compared. First we will examine the effect of using the “best” velocity simulation by applying each of the three calibration velocity sets to their appropriate range of discharges.

Return to the **\Models\Velocity Simulation\Velocity Calibration Set Assignments** tab and assign the appropriate cal set 1 to all discharges up to 75.2 cfs and cal set 2 to 139 cfs. Run the velocity simulation again by clicking the **Run** button in the **..\Options** tab. Then move to the **\Models\Habtae\Adjacent Velocity** tab and remove the check from the **Scan for velocity in adjacent cells** check box. Click the **Run** button in the **..\Output Options** tab. Move to the **ZHAQF Results** tab and copy the Results table for Bull Trout. Paste these results into the range beginning at row 72 in the adjhabvel.xls spreadsheet.

Compare the results of the standard habitat calculation for bull trout juveniles and adults (using the three cal set velocity simulation) to the standard habitat calculation using a single cal set. Are the results significant? How might this change in velocity simulation affect the outcome of any decision being based on the habitat analysis?

What effect does use of three cal sets have on adjacent velocity calculations? To examine this, move to the **\Models\Habtae\Adjacent Velocity** tab and check the **Scan for velocity in adjacent cells** check box. Click the **Run** button in the **..\Output Options** tab. Move to the **ZHAQF Results** tab and copy the results table for bull trout. Paste these results into the range beginning at row 91 in the adjhabvel.xls spreadsheet.

Again, compare the results using the graphs provided. Comparing these results with the results generated earlier using a single cal set, you can see that the effect of the adjacent velocity condition is greater at low flows in both sets of results. For this particular data set, it appears that the habitat results are more strongly influenced by the adjacent velocity condition than by the choice of velocity calibration set.

What about the first decision you made in the hydraulic modeling process, the choice of hydraulic model? The results obtained to this point were based on the “best” water surface results we could obtain by combining models at the control and across the pool. To examine the sensitivity of the habitat simulation process to choice of water surface model, we will run the WSL simulation using STGQ for all combinations of cross section and discharge.

Return to the **\Models\WSL\Methods** tab, select the **STGQ** radio button, and click the **Select All** button followed by the **Run** button. Move to the **..\Velocity Simulation** window and click the **Run** button in the **Options** tab. Next, move to the **\Models\Habtae\Output Options** tab and click the **Run** button there. Move to the **ZHAQF Results** tab and copy the Results table for Bull Trout. Paste the results into the space provided in row 113 of the adjvelhab.xls spreadsheet.

Comparing the graphs in spreadsheet you will again find that the choice of hydraulic simulation option has less effect than the choice of adjacent velocity calculation.

At least two conclusions can be drawn from this exercise. First, in the particular circumstances of this study site, the choice of hydraulic simulation has less influence than the choice of adjacent velocity conditions for Bull Trout adult and juvenile. This may not be true for all study sites or all HSC. (You may wish to create spreadsheet graphs for the other life stages to see if they are more or less affected by these choices.) Second, use of the adjacent velocity simulation can be a good tool to help determine which ranges of flow produce substantial and/or insignificant amounts of habitat when adjacent conditions are important. This information may be very useful in the instream flow decision arena.

When using conditional velocity based habitat simulation, it is especially important to ensure that the various adjacent velocity conditions used have a strong biological basis. The IFIM process emphasizes obtaining agreement among stakeholders as to the form of the analysis prior to beginning the PHABSIM application. This ensures that the critical questions about use of habitat simulation options such as conditional velocity are asked before the analysis begins.

Step 7. Including Adjacent Velocity Conditions That Lie Just Outside The Search Distance

As a final step in this laboratory, the **Scan for initial velocity (VO) and interpolate** radio button in the **..\\Habt\Adjacent Velocity** tab will be checked to cause the program to interpolate a weight for suitable habitat if the threshold velocity is not found within the user-specified scanning distance. In previous simulations, the **WUA = 0** radio button was checked, which caused the WUA to be set to 0.0 if the threshold velocity was not found. Choosing the interpolation option directs the program to locate a velocity that is closest to the threshold velocity and less/greater than the user specified velocity (V_o) within the scanning distance. The program then interpolates a '>combined suitability' between 0.0 and 1.0 to modify WUA in the computational cell rather than setting it to 0.0. Whether the program finds a suitable velocity which is less than (VLIM acts as a maximum) or greater than (VLIM acts as a minimum) V_o is determined by the option selected in the **Use VLIM as** box.

In PHABSIM for Windows, move to the **Models\\Habt\Adjacent Velocity** tab and enter V_o values of 0.4, 0.5, 1.0, 1.0 for bull trout fry, juvenile, adult, and spawning life stages, respectively, in the input table. Set **VLIM** to act as a minimum, select **Scan for initial velocity (VO) and interpolate**, and be sure that the **Scan for adjacent velocity** box is still checked. Move back to the **Output Options** tab and click **Run**. Copy and paste the ZHAQF table to row 137 of the **adjvelhab.xls** spreadsheet.

Note that V_o values have been entered for each life stage to be analyzed and, in this particular application, the values are less than the VLIM values since the minimum threshold option is being used in the simulations. Remember the minimum threshold option directs the program to look for values greater than VLIM so a relaxed V_o must be less than VLIM to make sense. Refer to the example in Chapter 4 of the manual if you have questions about this.

Plots of the **Scan for initial velocity (VO) and interpolate** and the **WUA = 0** options for adult and juvenile Bull Trout are included in the spreadsheet at row 130. The results for all life stages show slightly greater habitat over part of the range of discharges with the **Scan for initial velocity (VO) and interpolate** option compared to the **WUA = 0** option. This is a result of including the additional interpolated WUA that had weighting factors assigned between VLIM and V_o when the interpolation option was selected.

Laboratory 11. Habitat Modeling - HABTAM

Objective

The objective of this laboratory is to illustrate the use of the HABTAM program where the investigator wishes to examine available habitat at two different flows and the species and life stage of interest can migrate laterally within a cross section.

Programs Used: . HABTAM

Data Files Used: Lab11.phb

Introduction

The HABTAM program is used to simulate conditions at a cross section where fish are allowed to migrate laterally to find suitable habitat when two separate flows are compared. The user supplies a starting flow, an ending flow, and an appropriate maximum migration distance. The program will compute the WUA for each pair of discharges and compute the amount of WUA that is used at the ending flow assuming that all the WUA (i.e., habitat) at the starting flow was used. The program can also be used with a maximum allowable migration distance of 0.0, which might be appropriate for incubation life stages or benthic invertebrates. In this latter case, the program will compute the minimum of the WUA of the starting or ending flow. The use of the HABTAM program should not be confused with “migration” analyses within a reach or river segment, since only lateral migration on a given cross section is considered in the HABTAM program. PHABSIM for Windows does not contain any reach or river segment migration analytical capabilities.

The required hydraulic and channel properties information for this lab has already been generated in previous exercises. We will use the Lab11 project that contains three calibration sets assigned to their representative discharge ranges as the starting point for this lab. The laboratory implements the following processes four steps:

- Ensure the best WSL and velocity simulations have been performed
- Set HABTAM Options
- Simulate habitat using HABTAM

Step 1. Open the Lab11 Project

Use **/File/Open** to move to the lab11 working directory and open the lab11 project file. You now have the sample project as it was at the end of Lab 6 with the velocity distribution determined by three velocity templates applied to three ranges of flow.

For later use, it is a good idea to open the project and make a note of the curve ID numbers and which life stage and species they represent. Table L11-1 contains the curve ID numbers in the project. Note that some have three digits for the species ID number.

Table	Windows	DOS	Difference	% difference	
	Cell bed elevation	91.65	91.65	0	0.00
	Water surface elevation	92.456	92.47	0.014	0.02
	Depth	0.806	0.82	0.014	1.71
	Depth Suitability Index	0.0708	0.096	0.025	26.25
	Combined Suitability Index	0.0644	0.087	0.023	26.25
	Weighted Usable Area	8.698	11.79	3.096	26.25
	Acknowledgements				i
	PREFACE				ii
	A Brief History of PHABSIM				
	Use of this Document				
	Changes Between PHABSIM Version 2 and PHABSIM for Windows				
	Conventions Used in this Document				
	Chapter 1, Introduction to the Physical Habitat Simulation System				1
	Objectives				
	Associated Laboratory Exercises				
	An Overview of IFIM				
	The Purpose of PHABSIM				
	The Structure of PHABSIM				
	Application of PHABSIM				

L11-1. HSC ID numbers and life stages provided in the sample project.

Step 2. Set HABTAM Options

Go to **/Models/HABTAM/Options** and put a check in the boxes for **Write migration calculation details**, **Write cross section data**, **Write flow related data**, and **Write computational details**. Selecting these options will allow the examination of the computational details in the output file listing to better understand how the HABTAM program functions. Check that **Velocity Calculation Options** in the **Velocity Calculations** tab is set to **Mean column velocity** because the HSC curves used in the laboratory are based on mean column velocities. The remaining options can be left in their default condition. We recommend you compare the defaults with the option choices for a full understanding of the choices available in HABTAM.

Next, go to the **Migration** tab. Here you will find a table containing all species/life stages for which HSC have been entered in this project. You can supply the allowable migration distance for each life stage. For this lab we will use Brown Trout spawning, fry, and adults, HSC curve numbers 11300, 11301, and 11302. Enter migration distances of 0.0 for spawning, 5 for fry, and 15 for adults. Note that a distance of 0.0 is entered for spawning since incubating eggs cannot migrate.

In the **Options** tab you can enter starting and ending discharge pairs representing the range of flow to be considered in the analysis. In an actual application, you would enter flow ranges relevant to the purpose of your study. For example, the range of high and low flows due to a hydropeaking operation. For this lab, enter three sets of flow pairs: 15, 30, 75.2, 139, 250 versus 625; 15, 30, 75.2, 139, 250 versus 1,250 and 1,250 versus 15, 30, 75.2, 139, and 250. That is, enter a starting flow of 15 and an ending flow of 625. In the next row, enter a starting flow of 30 and an ending flow of 625, etc. For the third set, enter a starting flow of 1,250 and an ending flow of 15. Continue similar entries until finished.

Step 3. Simulate Habitat Using HABTAM

With these options selected, click the **Run** button. When the program finishes click **OK** and go to the **Migration Results** tab. There you will find a table of WUA values that reflect the amount of habitat area that was available to an organism that could migrate the specified distance when the flow changed over the ranges shown on the table axes. The **Graph** button provides 2- and 3-dimensional plots of the results. The entries in the **Migrations Results** table represent the habitat area derived for the species/life stage shown in the **Curve – species/life stage** box and the distance shown in the **Migration Distance** box. You may scroll through the possible entries for those boxes to view the results for all life stages and migration distances set in the options. For example, to view the table or graph for Brown Trout adults, scroll the species box to Brown Trout adults and the migration distance box to 15 ft. (We only specified a single entry of 15 feet for them earlier, so you must select that distance to fill the table with the Brown Trout Adult results.)

The ZOUTn file contains the selected output items and can be viewed using Wordpad. The Zout file contains computational detail summary tables for each cross section, a summary table output listing for the selected life stages for each set of paired flows for each cross section in sequence, and, following the final flow pair computational summary table for the current life stage, HABTAM provides reach level summary tables.

Examine the **Migration Results** tab summary table listing shown in Table L11-2 that contains the pair-wise flow comparisons for each life stage. It should be apparent from these results that the order of the paired flows can make a difference on program results. This should make sense since the initial flow is being compared to the ending flow and the actual difference is a function of not only the user-specified migration distance but also the combined suitability of available habitat cells at the ending discharge. Note that for both the adult and spawning life stages the “habitat used” areas are identical for these two sets of flow comparisons. For spawning, a migration distance of 0.0 should, by definition, produce the same result. In the case of adults, it is apparent that a migration distance of 15 feet is large enough to allow access to most, if not all, of the cross sections’ computational cells between the changes in discharge. Now select the spawning life stage and 0 migration distance. What kind of changes do you see in comparison to the adult migration habitat?

Table L11-2. HABTAM weighted usable area results for Brown Trout adults for the study site with 15 feet search distance.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Two- and 3-dimensional plots of the migration-based weighted usable area can be viewed by clicking the **Graph** button. The 3-D plot can be rotated for better viewing by holding down both mouse buttons and moving the mouse. It takes some trial-and-error experimentation to get familiar with the movement mechanism. Try it, and see.

The ZHAQF output from HABTAM contains the reach level summary results of WUA and can be accessed at the **ZHAQF Results** tab.

Step 4. Influence of Migration Distance on HABTAM Model Predictions

To illustrate the sensitivity of the HABTAM model to proper choices of migration distance, this step of the laboratory will alter the migration distance used for fry, juvenile, and adult life stages and compare the resulting computations at the 139 cfs and 15 cfs flow combinations. Change the migration distance for fry and adults to 3 feet and 25 feet respectively. The results of this change for Brown Trout adults are shown in Table L11-3.

What effect did changing the migration distances have on fry and adult life stages compared to the previous habitat simulations?

It should be apparent that sensitivity in model predictions occurs over a range of migration distance between 0.0 and some upper threshold that is dependent on the shape of the HSC criteria and, therefore, different for different species and life stages. The selection of an appropriate migration distance is a matter of professional judgment. Remember, this migration distance only applies to computational cells at a given cross section.

Table L11-3. HABTAM weighted usable area results for Brown Trout adults for the study site with 25 feet

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

search distance.

Laboratory 12. Habitat Modeling - HABEF

Objective

The objective of this laboratory is to illustrate use of the HABEF program for simulation of effective habitat for each of six options available to the user. The HABEF program can be used to examine differences between available habitat for a given species and life stage at different flows or comparisons between different species and life stages at a specific flow.

Programs Used: HABTAE, HABEF

Project Used: Lab12.phb

Introduction

The HABEF program can be used to examine a number of relationships between habitat conditions at two stream flows and/or for two life stages at a specific discharge. In this laboratory, each of the six computational options available within the HABEF program will be examined.

In the HABEF program different hydraulic property arrangements can be used depending on the option selected. The HABEF program will compute two different indices of habitat. The first is WUA, which is derived from the combined suitability factor computed by the initial habitat simulation program. (You must have run HABTAE or HABTAM prior to using HABEF.) The second index, UA (usable area) is derived from the sum of computational cell areas where the combined suitability in the computational cell is >0.001 . Usable areas can be considered to be a measure of the area where all of the HSC variables have suitability that is marginally greater than zero. Can you explain why this may not be the same as the wetted surface area of the stream?

The six steps in this laboratory guide the student through these basic options of the HABEF program:

- Union of Life Stage 1 with Life Stage 2
- Stream Flow Variation Analysis (Minimum WUA)
- Competition Analysis
- Stream Flow Variation Analysis (Maximum WUA)
- Effective Spawning Analysis
- Stranding Index Analysis

Step 1. Ensure Needed Hydraulic And Habitat Model Results Have Been Run

Habitat analysis results from HABTAE or HABTAM are required prior to executing HABEF. Open the Lab12.phb project in the Lab12 directory and note that **WUA Results** exist for Rainbow Trout adult. This indicates one or the other of these programs has produced results earlier. If you are uncertain which program was used, check the **Habitat Results** table. In this case, the **Habitat Results** table in the HABTAM window is filled with [NULL] entries while the table in the HABTAE window has numerical values. Hence, HABTAE was run.

Step 2. Set Appropriate Simulation Options and Run HABTAE Model

This step is provided as an example of the actions you would perform when the initial modeling steps have not yet been performed. For this laboratory, you may go directly to Step 3 as the HABTAE model has been run and the needed result files are already in the Lab12 folder.

Move to the HABTAE program window by clicking **/Models/HABTAE**. Go to the **Life Stages** tab and click as many life stages on or off until only the Brown Trout adult and Rainbow Trout adult (or other desired) life stages remain. Click the **Run** button to run the model. You will now have habitat results for adult Brown and Rainbow trout.

At this point, two files have been created in the Lab12 directory containing computational cell details at each cross section for each simulated discharge for each of the species and life stages used in the simulation. Those files have the naming convention: Projectname.HSCnr(e or m). The habitat suitability criteria number (HSCnr) is used to identify species and life stage contained in each particular results file. The suffix „e’ or „m’ indicates whether the files were produced by HABTAE or HABTAM, respectively. The HABEF program uses these files for cell-by-cell computations. In this case, they should be named Lab12.11302e and Lab12.21115e, respectively, for Brown and Rainbow trout adult results produced by HABTAE.

Step 3. HABEF Simulations for Union (Option 1) and Competition (Option 3) Analyses

The HABEF program will now be used to simulate the union of two life stages and competition between two species. In the union analysis for two species and life stages (Option 1) HABEF computes total weighted usable area represented by combined habitat of the two species or life stages. The total habitat quantity computed at a specific discharge will always be greater than or equal to the highest amount for a single species or life stage but always less than or equal to the sum of the two habitat totals. Why is this? In answering this question, consider adding the largest WUA value regardless of species in each cell to the HABEF union sum. If species/life stage “a” has the dominant WUA in all cells and there are no cells where the species/life stage “b” alone has WUA greater than zero, then the WUA reported by HABEF will be equal to the WUA for species/life stage “a”. If both species/life stages dominate in some cells, the sum will be greater than the sum for species/life stage “a” alone. Will this general statement still be true for two species/life stages that use very different habitats with little or no overlap?

The analysis of competition (Option 3) computes the amount of habitat for a particular species or life stage for two conditions. First, it calculates habitat for species/life stage “a” in cells where habitat for the species/life stage “b” is zero. This is combined with the amount of habitat occurring in computational cells where combined suitability is greater than 0.0 for both species but where species “a” has a higher combined suitability value than species “b”. Thus, the competition option describes the total WUA for cells where a species dominates.

Select **/Models/HABEF** and enter a descriptive name for the comparison being run in the **Job Title** text entry box. This name will be used to label all output tables (both text files and on-screen). In the species/life stage 1 text entry box, click the down arrow button to the right and select Brown Trout adult. In the second text entry box, click the down arrow and select Rainbow Trout adult, then click the **Union of life stage 1 with life stage 2** radio button. Note that this assigns Brown Trout adults to species/life stage 1 and Rainbow Trout adults to species/life stage 2. Finally, click the **Run** button and view the **Results** tab. You may also produce a named HABEF results file using the **Text File** button in the **Results** tab and view it using Wordpad. PHABSIM for Windows does not retain subsequent sets of results in the database, so it is convenient to create result text files for

each run to allow later comparison when numerous HABEF options are generated in the course of an analysis. It is also wise to change the job title for each run to avoid later confusion among options where the numerical results are similar.

The table in the **Results** tab contains a summary for each life stage at each discharge of their respective UA and WUA values and the WUA associated with the union of the two life stages. Note that the WUA associated with the union of two life stages is less than the total WUA if the two life stages had been simply added together at a given flow. A comparison of the Total Area column (i.e., total stream surface area) and the respective UA columns for each life stage shows that at discharges below 139 cfs all computational cells have a combined suitability greater than 0.001. Why is this?

Table L12-1 contains an example of the union analysis output table. Click the **Graph** button at the bottom of the HABEF **Results** tab to view graphical results.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Table L12-1. HABEF output for union analysis.

You can see that the total amount of WUA in the union of two species is greater than that for either individual species WUA and less than their sum would be. You may wish to view the graph of results and print it for later reference.

Next, the HABEF program will be run again with the same input data but will be used to compute effective habitat based on selection of the competition analysis option.

Go to the HABEF **Options** tab and select the **Competition analysis** radio button. Make sure that the first input file is ZHCF1 and the second file is ZHCF2, as in the previous example. Change the **Job Title** to indicate the next results are for the competition analysis. Click the **Run** button and move to the **Results** tab.

Table L12-2 shows output from the competition analysis. Note that the HABEF output is different when selecting competition analysis versus union analysis (Table L12-1). The program shows summary results at each simulation discharge in terms of total stream area, UA and WUA where each species has the only suitable habitat. Summary output is also provided for amount of usable area for both species and area associated with habitat conditions where each species is dominant (i.e., combined suitability for species “1” is greater than the combined suitability for species “2”). The program also computes the amount of habitat area with equal worth for both species as noted earlier.

Table L12-2. HABEF output for competition analysis.

Windows		DOS	Difference	% difference
Cell bed elevation	91.65	91.65	0	0.00
Water surface elevation	92.456	92.47	0.014	0.02
Depth	0.806	0.82	0.014	1.71
Depth Suitability Index	0.0708	0.096	0.025	26.25
Combined Suitability Index	0.0644	0.087	0.023	26.25
Weighted Usable Area	8.698	11.79	3.096	26.25

Acknowledgements

i

PREFACE

ii

A Brief History of PHABSIM

Use of this Document

Changes Between PHABSIM Version 2 and PHABSIM for Windows

The competition results for 15.0 and 30.1 cfs show Brown Trout adults have more suitable habitat at the low flow range. However, from 75.2 cfs and up, Rainbows have significantly more habitat than Browns.

The dominance of Rainbow Trout adult habitat at higher discharges is related to their tolerance for lower depth as reflected in the depth HSC reaching 1.0 at a lower depth for Rainbows than for Browns. Go back and check the HSC to confirm this. For the 15 and 30.1 cfs discharges, Rainbow Trout adults have between 50% and 70% as much habitat as Brown Trout adults. However, from 75.2 cfs and up, the Rainbow habitat is three or more times as abundant as Brown habitat. Assuming the HSC have been verified to accurately describe behavior of the two species, from these results can you conclude that higher flows favor Rainbow Trout adults? How would the results be affected if the depth HSC for each species had a $\pm 25\%$ error and the full range of the uncertainty was considered in the analysis?

Step 4. Streamflow Variation Minimum and Maximum Analysis

Streamflow variation analysis for minimum and maximum WUA in HABEF can be used to explore which species and life stage has either the maximum or minimum WUA at each discharge on a computational cell-by-cell basis. When HABEF minimum variation is selected, the composite suitability factor used to compute WUA for a computational cell is the minimum composite suitability value in that computational cell in each of the two species/life stages being compared. The maximum streamflow variation HABEF option is identical except that the maximum composite suitability from the computational cell within the two ZHCF files is used to compute WUA.

Make sure that the first species/life stage you wish to consider is entered in the first dialog box and the second species/life stage is in the second box. Select the **Streamflow Variation Analysis (minimum WUA)** radio button, change the job title to indicate minimum WUA analysis, and click the **Run** button to execute the HABEF program. Move to the Results tab to view the output. You may wish to save the results for later comparison, click the **Save** button to do so.

For comparison, perform a maximum streamflow variation analysis. Enter a job title indicating maximum WUA, click the **Streamflow Variation Analysis (maximum WUA)** radio button, and click **Run**. Again, click the **Results** tab to review results.

A comparison of these streamflow variation results with the previous minimum analysis shows a marked difference in the relationship between minimum or maximum WUA and discharge. The minimum WUA analysis declines as discharge increases, while maximum WUA increases then decreases with flow.

When these results have been examined, return to the HABEF window.

Step 5. Effective Spawning Analysis Using HABEF

HABEF effective spawning analysis allows an investigator to examine the effects of flow alterations on spawning and incubation life stages. The program computes effective spawning habitat based on the concept that available habitat at an initial (spawning) discharge must also be available at the second (incubation) discharge. In this analysis, the HABEF program computes combined suitability in a computational cell at the starting and ending discharges (i.e., for each set of paired discharges in respective HABTAE or HABTAM results). If composite suitability at the second discharge is greater than 0.0, then the composite suitability factor for that computational cell at the first or starting discharge remains unchanged and WUA for that computational cell is added to the total for the cross section and, hence, the reach. Simply put, if the spawning area maintains minimal incubation conditions (stays wet with needed velocity) then the spawning area is accumulated in the total. However, if the composite suitability factor at the second discharge is 0.0, then suitability at the first discharge is set to 0.0 and that amount of available habitat is 'removed' from the total at the cross section. This is similar to using the minimum streamflow analysis option but differs in that WUA at the first flow is dependent on the analysis of the second flow.

To make this example of effective spawning more realistic, new results using Bull Trout spawning HSC will be generated with the HABTAE program.

Return to **/Models/HABTAE**, move to the **Life Stages** tab and click all of the Brown and Rainbow Trout life stages to turn them off. Now click the four Bull Trout life stages to turn them on. Click **Run** and return to the HABEF program when HABTAE is finished.

Change the job title to indicate you are performing an effective spawning analysis and select Bull Trout spawning in both species/life stage dialog boxes. Then click **Run** and move to the **Results** tab. Click the **Graph** button to view the results. Which combination of discharges produces the greatest effective spawning habitat values? Which produce the lowest values?

The plot also shows that if the starting flow is 1250.0 cfs and flows are reduced, the amount of effective spawning habitat is substantially reduced at 250.0 cfs and non-existent below 75.2 cfs. As the starting and ending flow difference is reduced, the effective spawning is less affected as would be expected (Why?). It should also be apparent that starting at a lower flow such as 75.2 and ending at a higher flow such as 139.0 cfs has less impact on effective spawning (Why?). If you have difficulty reading the 3-dimensional plot, return to the results table and examine it in drawing your conclusion.

Step 6. Stranding Index Analysis Using HABEF

Stranding analysis with the HABEF program employs essentially the same computational logic as described above for effective spawning analysis. The composite suitability of a computational cell at the second flow must be greater than 0.0 for composite suitability of the computational cell at the first flow to contribute to effective WUA. Thus, when evaluating stranding, one should only compare flow pairs that show a decrease in discharge. For this analysis, the same species and life stage is selected in both dialog boxes on the **/HABEF/Options** tab. Typically, the selected life stage would be one that has only a small capacity to move with changes in discharge, though the analysis can be conducted for any life stage.

While a stranding analysis will not be run in the laboratory due to time considerations, the following general approach can be used for all life stages. To ensure that the analysis is focusing on available depth alone, you can create a new set of suitability curves for stranding. To do so, make copies of the HSC in the **/Edit/Suitability Curves** window and edit suitability curve coordinates for velocity and channel index, setting all suitability values are 1.0. There is no need to change the number of coordinate pairs. Change depth suitability curve coordinates for depth such that depth suitability is 0.0 below some threshold (e.g., 0.5 feet) and then change the remaining depth SI values to 1.0.

Save these changes and run the new HSC in the HABTAE program. Then move to the HABEF program and run the stranding index analysis using the same HSC in both dialog boxes. The results will show the chance of stranding when depth for that species/life stage drops below the selected threshold value.

▪ 枕最甄嫩攀.....

.....

.....

.....

.....

.....

.....

.. .. .

.....

.....

.....

.....

.....

.....

.....

.....

..

.....
.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

APPENDIX – F

Riverine Fish Flow Investigations

Federal Aid Project F-289-R6

Richard Anderson
Principal Investigator

and

Greg Stewart



Russell George, Director

Federal Aid in Fish and Wildlife Restoration

Job Progress Report

Colorado Division of Wildlife

Fish Research Section

Fort Collins, Colorado

June 2003

STATE OF COLORADO

Bill Owens, Governor

COLORADO DEPARTMENT OF NATURAL RESOURCES

Greg Walcher, Executive Director

COLORADO DIVISION OF WILDLIFE

Russell George, Director

WILDLIFE COMMISSION

Rick Enstrom, Chair
Marianna Raftopoulos
Tom Burke
Jeffrey A. Crawford
Philip James

Robert Shoemaker, Vice-Chair
Bernard Black
Brad Phelps
Olive Valdez
Don Ament, Dept. of Ag.

AQUATIC RESEARCH STAFF

Mark S. Jones, General Professional VI, Aquatic Wildlife Research Leader &
F-241 Boreal Toad Conservation
Richard Anderson, General Professional IV, F-289 Riverine Fish/Flow Investigations
Stephen Brinkman, Laboratory Technician II
Patrick Davies, Physical Science Researcher IV, F-243, Water Pollution Studies
Patrick Martinez, General Professional V, F-242, Coldwater Reservoir Ecology &
F-325 Westslope Warmwater
R. Barry Nehring, General Professional V, F-237, Stream Fisheries Investigations
George Schisler, General Professional IV, F-394, Salmonid Disease Investigations
Kevin Thompson, General Professional IV, F-237, Stream Fisheries Investigations
Rod Van Velson, General Professional IV, F-161, Stream Habitat Investigations
and Assistance
Harry Vermillion, Scientific Programmer/Analyst, F-239, Aquatic Data Analysis
Rosemary Black, Program Assistant I

Paula Nicholas, CDOW Federal Aid Coordinator
Jackie Boss, CDOW Librarian

State: Colorado

Project No. 7400 ENDG 0700

Name: Aquatic Nongame Research

Study No. SE-3-22

Title: Riverine Fish Flow Investigations

Period Covered: July 1, 1997 - June 30, 2002

Study Objective: To determine relationships between flow and habitat availability for warm-water riverine fish communities of Colorado.

Prepared by: _____
Richard Anderson, Wildlife Researcher

Approved by: _____
Mark Jones, Aquatic Wildlife Research Leader

Date: _____

Job Progress Reports are preliminary and subject to change. They may not be published or cited without permission of the Director. The results of the research investigations contained in this report represent work of the authors and may or may not have been implemented as Division of Wildlife policy by the Director or Wildlife Commission.

TABLE OF CONTENTS

APPROVAL PAGE	ii
LIST OF TABLES	v
LIST OF FIGURES	vii
LIST OF APPENDIX TABLES	ix
LIST OF APPENDIX FIGURES.....	x
INTRODUCTION	1
STUDY AREA	4
METHODS	12
Fish Sampling	12
Channel Topography.....	14
Hydraulic Simulation	19
Habitat Quantification.....	20
Development of Meso-Habitat Suitability	20
Determination of Habitat Availability	22
RESULTS	23
Fishery Quantification	23
Fish Over 15-cm in Length	23
Fish Less Than 15-cm in Length	28
Size Structure for Native Fish.....	30
Density and Biomass Estimation	34
Habitat Quantification.....	39
General Site Description.....	39
Habitat Composition and Diversity	40
Habitat Suitability	44
Habitat Availability Versus Flows.....	47
DISCUSSION	62
Habitat Modeling, Flow Needs for Native Sucker	62
Habitat Composition and Diversity	65
Field Observation, Flow Needs of Native Fish.....	66
Non-Native Fish Versus Flows.....	68
Flow for Endangered Fish.....	69

FLOW RECOMMENDATIONS	70
Colorado River.....	70
Yampa River	71
Dolores River.....	72
SUMMARY	73
CONCLUSIONS	74
RECOMMENDATIONS FOR FUTURE RESEARCH.....	75
ACKNOWLEDGEMENTS.....	76
REFERENCES	77
APPENDIX TABLES AND FIGURES	82

LIST OF TABLES

1.	Recommended mean monthly flows [Osmundson et al (1995)] for the 15-Mile Reach in cubic ft/sec.	10
2.	Mean monthly and monthly minimum flows recorded at the Palisade gage, 15-Mile Reach, Colorado River for summer months during the three years of the study.	11
3.	Dates for electro-fishing and flows on the day of the sample.	15
4.	Depth and velocity criteria used to define meso-habitat types.	21
5.	Species composition for fish over 15 cm from all study sites.	25
6.	Species composition from seine hauls at the Sevens and Duffy sites in 1999 and 2001, Yampa River.	29
7	Species composition for fish greater and less than 15 cm at the Big Gypsum site on the Dolores River, July 2001.	30
8.	Mean lengths of bluehead sucker captured during the study period (1998 to 2001) in the Yampa, Colorado and Dolores Rivers.	31
9.	Mean lengths of flannelmouth sucker captured during the study period (1998 to 2001) in the Yampa, Colorado and Dolores Rivers	33
10.	Mean lengths of roundtail chub captured during the study period (1998 to 2001) in the Yampa, Colorado and Dolores Rivers.	33
11.	Density and biomass estimates in fish per kilometer and kilograms per kilometer for each study site.	36
12.	Density and biomass estimates in fish per hectare and kilograms per hectare for each study site.	37
13.	Physical attributes of each study site (mean velocity, length, mean width, surface area at modeled flows)	41
14.	Meso habitat availability per kilometer at a reference flow typical of the base flow period.	42
15.	Correlation between riffle meso habitat and total fish biomass.....	43

16.	Correlation between pool habitat and biomass for carp, white sucker and catfish	43
17.	Correlation between deep riffle habitat and bluehead sucker biomass.....	44
18.	The 1, 10, 20, 40, 60, 100 and 177 low flow day for the Maybell, Lily Park, Palisade and Bed Rock gages for years with fishery biomass data.	54

LIST OF FIGURES

1.	Location of the three study sites for the Yampa River, Lily Park, Sevens and Duffy.....	5
2.	Peak flow during the study period recorded at the Maybell gage with exceedence frequency for the period of record.....	7
3.	Minimum flow during the study period recorded at the Maybell gage with exceedence frequency for the period of record.....	7
4.	Location of the two study sites in the 15-Mile Reach, Colorado River, Corn Lake and Clifton.	9
5.	Location of the Big Gypsum (Big Gypsum Valley) study site on the Dolores River.....	12
6.	Example of digitized polygons for electro-fishing areas (photo of Clifton site).	22
7.	Bluehead Sucker depth and velocity criteria used to model bluehead habitat availability.	45
8	Flannemouth sucker depth and velocity criteria used to model flannemouth habitat availability.	46
9	Bluehead sucker habitat availability at Corn Lake, Colorado River.	48
10.	Bluehead sucker habitat availability at Clifton, Colorado River.	48
11.	Bluehead sucker habitat availability at Lily Park, Yampa River.....	49
12.	Bluehead sucker habitat availability at Sevens, Yampa River.	50
13.	Bluehead sucker habitat availability at Duffy, Yampa River	50
14.	Bluehead sucker habitat availability at Big Gypsum, Dolores River.	51
15.	Projected biomass (kg/ha) of bluehead sucker based on habitat availability over a range of simulated flows.	53
16.	Projected versus observed bluehead biomass for five study sites.....	55
17	Flannemouth sucker habitat availability at Corn Lake, Colorado River	56

18.	Flannelmouth sucker habitat availability at Clifton, Colorado River	57
19	Flannelmouth sucker habitat availability at Lily Park, Yampa River.....	57
20.	Flannelmouth sucker habitat availability at Sevens, Yampa River	58
21.	Flannelmouth sucker habitat availability at Duffy, Yampa River	59
22.	Flannelmouth sucker habitat availability at Big Gypsum, Dolores River	59
23.	Projected flannelmouth biomass as a function of flow for all study sites	60
24.	Projected versus observed flannelmouth biomass for five study sites.....	61

LIST OF APPENDIX TABLES

1.	Density and biomass estimates for all species in fish per kilometer in kilograms per kilometer for each study site	83
2.	Density and biomass estimates for all species in fish per hectare and kilograms per hectare for each study site	85
3.	Corn Lake polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker	87
4.	Clifton polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker	88
5.	Lily Park polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker	89
6.	Sevens polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker	90
7.	Duffy polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker	91

LIST OF APPENDIX FIGURES

1.	Longitudinal profile for Corn Lake site, Colorado River.	92
2.	Longitudinal profile for Clifton site, Colorado River.	92
3.	Longitudinal profile for Lily Park site, Yampa River.....	93
4.	Longitudinal profile for Sevens site, Yampa River	93
5.	Longitudinal profile for Duffy site, Yampa River	94
6.	Longitudinal profile for Big Gypsum site, Dolores River	94
7.	Corn Lake study site meso-habitat distribution at 1000 cfs, Colorado River	95
8.	Clifton study site meso-habitat distribution at 1000 cfs, Colorado River.....	95
9.	Lily Park study site meso-habitat distribution at 200 cfs, Yampa River	96
10.	Sevens study site meso-habitat distribution at 200 cfs, Yampa River	96
11a.	Meso-habitat availability for modeled flows at Corn Lake	97
11b.	Shannon Diversity, Interspersion and Juxtaposition for modeled flows at Corn Lake.....	97
11c.	Meso-habitat availability for modeled flows at Clifton.....	97
11d.	Shannon Diversity, Interspersion and Juxtaposition for modeled flows at Clifton	97
12a.	Meso-habitat availability for modeled flows at Lily Park	98
12b.	Shannon Diversity, Interspersion and Juxtaposition for modeled flows at Lily Park.....	98
12c.	Meso-habitat availability for modeled flows at Sevens	98
12d.	Shannon Diversity, Interspersion and Juxtaposition for modeled flows at Sevens	98
13a.	Meso-habitat availability for modeled flows at Duffy.....	99

13b.	Shannon Diversity, Interspersion and Juxtaposition for modeled flows at Sevens	99
13c.	Meso-habitat availability for modeled flows at Duffy.....	99
13d.	Shannon Diversity, Interspersion and Juxtaposition for modeled flows at Duffy	99
14.	Sigma plot for bluehead (left) and flannelmouth (right) sucker, showing biomass at mean polygon depth (x-axis) and velocity (y-axis).	100

INTRODUCTION

Conservation and management of native species is now a major consideration within the Colorado Division of Wildlife (CDOW). This is especially true for species that are listed as federally threatened or endangered. Four species of fish in the Colorado River basin are listed as endangered by the U.S. Fish and Wildlife Service. The Upper Colorado River Recovery Program was established to identify and resolve problems, so these fish can eventually be down-listed (Wydoski and Hamill 1991). The state of Colorado and the Recovery Program share the same goal of recovering the fish, but their agencies may not share common strategies. A unifying approach for native fish management objectives is to agree on the scientific validity of data involved in identification of limiting factors.

In Colorado State government instream flow protection for fish via water rights has been a common practice in high elevation headwaters (Espregren 1998). Water rights adjudication, however, has become a rigorous legal process for high profile warm water rivers like the Colorado and Yampa Rivers where water is already highly over-appropriated. In response, U. S. Fish and Wildlife Service (USFWS) conducted studies for instream flow recommendations in regard to recovery of endangered fish species in the 15-Mile Reach of the Colorado River (Osmundson et al. 1995) and the Yampa River (Modde and Smith 1995). Modde et al. (1999) was a field-based study on the Yampa River, also sponsored by the Recovery Program. Even though the intent of these flow studies was the same, to determine stream flow requirements for endangered fish, recommendations were based on vastly different methodologies.

The goal of this project was to develop biologically based instream flow recommendations for the Colorado in the 15-Mile Reach and Yampa rivers based on habitat and flow requirements for non-endangered native fish. The identification and validation of flow needs for non-endangered native fish may assist in preventing listing these species in the future. This data may also be of value to the Endangered Fish Recovery Program by providing ancillary information concerning the overall fish community and descriptions of physical habitat availability.

Typically CDOW uses the R2Cross method (Nehring 1979) or PHABSIM (Bovee 1982) for making instream flow recommendations for protecting cold water habitats. However these two methods were not considered appropriate for the warm water sections of the Colorado and Yampa Rivers given the elevated levels of biological, geomorphic and social complexities for these rivers.

This study employed a Meso-Habitat approach that is similar in concept to PHABSIM. PHABSIM is widely used in North America to quantify impacts of altered flow regimes to habitat. PHABSIM consists of two modeling components. The hydraulic component is a series of one-dimensional cross-sections that are linked to produce a series of rectangular cells that form a grid. Mean depth and velocity conditions are calculated for each cell for a given flow. The biological component is a set of suitability index curves for depth and velocity criteria that are used to rate micro-habitat suitability for each cell in the cross-sectional grid. Habitat availability is measured by an

index called weighted useable area (WUA), the summation of cell areas weighted by its suitability index. When plotted versus discharge WUA typically peaks at a single flow that is considered the flow that maximizes habitat. PHABSIM has been criticized because of assumptions implicit with micro-habitat suitability curves, assumptions of positive relationships between habitat availability and fish abundance, and the tendency of users to recommend flows at the peak of the WUA-discharge relation regardless of natural flow occurrence. These assumptions have been obstacles for using PHABSIM to model impacts of reduced flows on large warm water rivers of the west slope (Rose and Hahn 1989).

The Meso-Habitat method of this study is also an integration of hydraulic and biologic analyses. We used a 2-D flow model to simulate depths and velocity. Fish habitat suitability was derived from density estimates made at each site. Two-dimensional (2-D) flow models have been found to have high potential for application in instream flow studies (Leclerc *et al.*, 1995; Bovee, 1996; Kondolf *et al.* 2000). Two-dimensional models offer a significant improvement over one-dimensional (1-D) modeling by increasing spatial resolution. This allows for a highly accurate quantification of the physical habitat for each flow of interest. 2-D models are not dependent on micro-habitat suitability curves for predicting habitat availability. Meso-habitat scale precision is more efficient for sampling biological data. Criteria can be established for individual species and also by guilds (sympatric species) (Parasiewicz 2001). A relationship between habitat availability to fish abundance assumes that fish distribute themselves in the river primarily as a function of habitat. A large part of this study was to develop meso-habitat criteria for two native suckers. This was accomplished by examining the relationship between their abundance and meso-habitat availability. The output of the meso-habitat methodology was the relationship among meso-habitat availability and the range of modeled flows.

Species Used for the Biological Analysis

The primary species used in the instream flow analysis were the bluehead sucker (*Catostomus discobolus*), flannelmouth sucker (*Catostomus latipinnis*) and roundtail chub (*Gila robusta*). These species, quite common in the Colorado River, comprised about 80 percent of fish sampled between Rifle and Palisade. Anderson (1977) speculated that fishery abundance was likely at carrying capacity set by the physical habitat. Samples made by the Recovery Program (ISMP) in the Colorado River downstream of Grand Junction to Loma found native fish were about 90% of the catch (Elmbald 2003). Osmundson (1999) reported high catch rates of native suckers in the Colorado River, with the highest catch rate in the 15-Mile Reach. The thriving populations of these three native species suggest that habitat, base flow alternations or non-native introductions have not negatively impacted their life history requirements in the river. In fact, studies suggest the Colorado River is an excellent location to study dynamics between these three native fish and physical habitat.

Conversely, these three native species have not maintained a historically abundant population or relative composition in the Yampa River. Miller (1982), Carlson (1979), Wick (1981 and 1986) and Prewitt (1977) reported that native suckers had become fairly rare in the Yampa River upstream of Maybell at River Mile (RM) 74. The most common species is the introduced white sucker (*Catostomus commersoni*). Elmlblad (2003) reported native fish were only 24% and 35% of the catch during Interagency Standardized Monitoring Program (ISMP) surveys upstream of Maybell (River Mile 75). The Yampa River has experienced reduced base flows and has an established population of introduced nonnative predators, which obscure determination of the relationship between habitat and native fish density.

The bluehead sucker is a large fish (up to 45 cm in length) that remains abundant in most west slope rivers. Not a lot of data is available from life-history studies of the bluehead sucker. However, biologists who sample in the Colorado drainage strongly associate this species with a single meso-habitat. This makes the bluehead sucker an excellent species for flow and habitat evaluation studies. Adult fish are typically found in moderate to deep riffle habitat, which is a combination of fast flowing water over cobble-rubble substrate (Woodling 1985; Sublette 1990). The bluehead feeds on invertebrates, which have their highest densities in riffles. Because the bluehead is an obligate riffle species, its meso-habitat suitability can be defined by the depths and velocities of the riffle habitats the sucker occupies.

The flannemouth sucker is another large bodied fish that grows up to 60 cm long. The flannemouth is abundant in most west slope rivers where hybridization with white sucker has not occurred. The flannemouth is another species whose habitat requirements can be defined by depth and velocity combinations. Adults of generally occupy deeper run habitats (Woodling 1985). Runs are typically defined as areas with low to moderately fast currents. In the Colorado and Yampa Rivers, run habitat is generally more ubiquitous. Likewise, the flannemouth tends to be more common in run dominated rivers. The flannemouth's habitat overlaps with the bluehead's in the glide section of the river. Glides have similar depths and velocities as runs, but glides are located between the tail of the pool and the head of a riffle where bed elevation is rising.

The roundtail chub is a cyprinid that achieves a large body size (up to 45 cm in length) and is still fairly common in parts of its range in Colorado. The roundtail chub is a predator and has a much different life history and behavior than the two native suckers. These fish generally seek cover during the day and patrol or forage during the evening. These fish do not rely on one particular meso-habitat type; therefore, their habitat use can not be modeled by a simple range of depth and velocity criteria. This is a true multi-meso-habitat species. Factors that control their density may be more a function of forage availability than of meso-habitat availability.

The speckled dace (*Rhinichthys osculus*) is a small-bodied cyprinid that may attain a length of 12-cm (Woodling 1985). Speckled dace are generally very abundant and like the bluehead sucker are a riffle-obligate species. Since dace are small-bodied fish they can occupy shallow riffles, which means during periods of reduced flows

bluehead sucker habitat would become unsuitable long before dace habitat loss would become problematic. Therefore, meso-habitat availability for speckled dace and another small-bodied native fish, the mottled sculpin (*Cottus bairdi*) were not modeled in this study. It was necessary, however, to include these species in an ancillary analysis because the dace and sculpin populations have been noticeably impacted on the Yampa River during low-flow scenarios.

Study Objectives:

- 1). Quantify fish habitat on warm water sections of the Yampa, Colorado and Dolores rivers using 2-D flow models
- 2). Determine community structure, density and biomass for fish assemblages for the three study rivers
- 3). Determine relationships between habitat availability and fish abundance for the native species bluehead sucker, flannelmouth sucker and roundtail chub
- 4). Develop biologically based instream flow recommendations for the Yampa River and Colorado Rivers in the 15-mile reach
- 5) Provide validation for meso-habitat suitability values used in the 2-D model and for predicting habitat as a function of flow

STUDY AREA

Yampa River

There are three study areas on the Yampa River. The two sites established in 1998 are called the Sevens and Duffy stations. A third site at Lily Park was added in 2000. The Sevens station is located at River Mile (RM) 63 and is 1.8 mile in length. Duffy is at River Miler (RM) 109 and is 1.3 miles in length (Figure 1). Sevens and Duffy were electro-fished in 1998, 1999, 2000 and 2001. The habitat was mapped in 1999. The Lily Park site is located just below Cross Mountain Canyon and just above the mouth of the Little Snake River (Figure 1). The Lily Park site extends 19 miles from RM 52.7 to RM 54.5. The bridge on County Road (CR) 25 is located at RM 52.5.

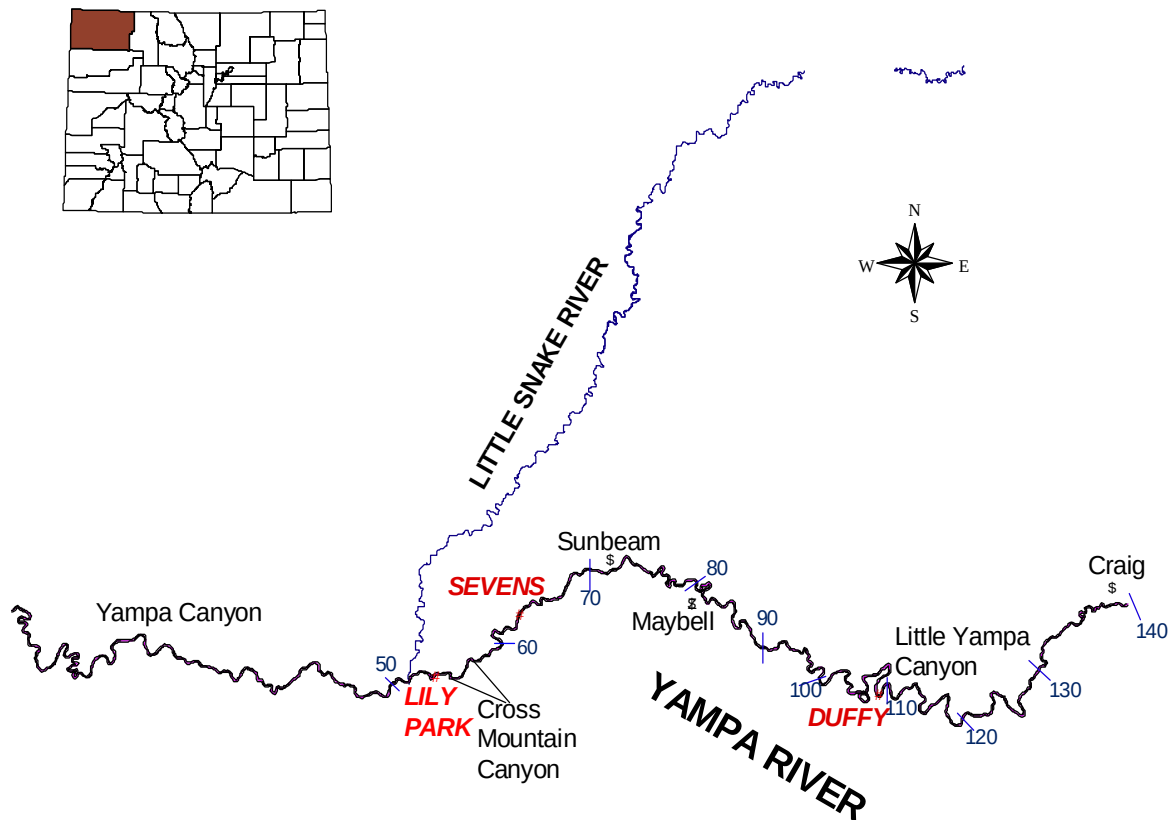


Figure 1. Location of the three study sites for the Yampa River, Lily Park, Sevens and Duffy.

The Cross Mountain Ranch is the landowner for most of the river at Sevens and Lily Park. The BLM is the primary landowner at Duffy. In general, each site on the Yampa River has distinctly different fish and habitat characteristics. Duffy is located in Little Yampa Canyon and has some deep pools with large boulders that provide cover. Duffy is low gradient. The primary habitat during the base-flow period consists of shallow pools. Sevens is also low gradient with gravel-sand substrate. At typical base flows, shallow, low-velocity pools and runs are the most common habitats. The Lily Park site is higher gradient with a cobble-boulder substrate. Faster flowing habitats (runs and riffles) dominate in Lily Park. The Lily Park site was added because of its better native fish composition than at Duffy.

Peak flows recorded at the Maybell gage were fairly similar for the years 1998, 1999 and 2000, at 10,040 cfs, 9,980 cfs and 9,830 cfs respectively. Peak flows in these three years are near the magnitude of the median peak flow of 9,980 cfs for the 86 year period of record (Figure 2). Peak flow in 2001 was 7,650 cfs, which has been exceeded in 77% of the years during the period of record. The peak flow in 1997 was 16,400, and has been exceeded in only 5% of the period of record (Figure 2). Andrews (1982) calculated bankfull flow for the Yampa from the Maybell gage to be 9,000 cfs.

Determining impacts of low flows are one of the primary objectives of this study. Modde et al. (1999) used a cross section methodology (modified R2Cross) to identify habitat availability at low flows for endangered fish on the Yampa River. The result was a recommendation that 93 cfs be used as a reference flow that signals the beginning of severely degraded conditions. The 93-cfs reference flow was specifically not meant to be an instream flow recommendation since it was believed the endangered pikeminnow could likely survive severely degraded conditions for a short term.

Annual minimum flows recorded at the Maybell gage for 1997, 1998, 1999, 2000 and 2001 were 320 cfs, 115 cfs, 166 cfs, 30 cfs and 50 cfs respectively. The 86-year median minimum flow is 126 cfs (Figure 3). The 2000 minimum flow of 30 cfs was exceeded in 93% of the years, and the 2001 minimum flow of 50 cfs was exceeded in 83% of the years for the period of record (Figure 3). Flow did not drop below the 93-cfs reference flow in 1998 and 1999, but flow was less than 93 cfs for 34 days in 2000 and 17 days in 2001.

Two consecutive years of low flow may have more significant and lasting impacts on the aquatic community (carrying capacity) than a single low flow year. Stream flow was less than the 93-cfs reference flow for 0 days in 1997, 2 days in 1996, 0 days in 1995. In 1994, the minimum flow was 8 cfs and flow was less than 93-cfs for 73 days that year. Presumably habitat was severely restricted in 1994 and there were impacts to the fish community. The four-year interval between 1994 and the start of sampling in 1998 may have been enough time to allow the fish community to adjust back to normal flows. There were two days of flow below the 93 cfs in 1996. As of 2000, flow had not been below the 93 cfs for the previous three years. However, 2001 was a second consecutive low-flow year (Figure 3).

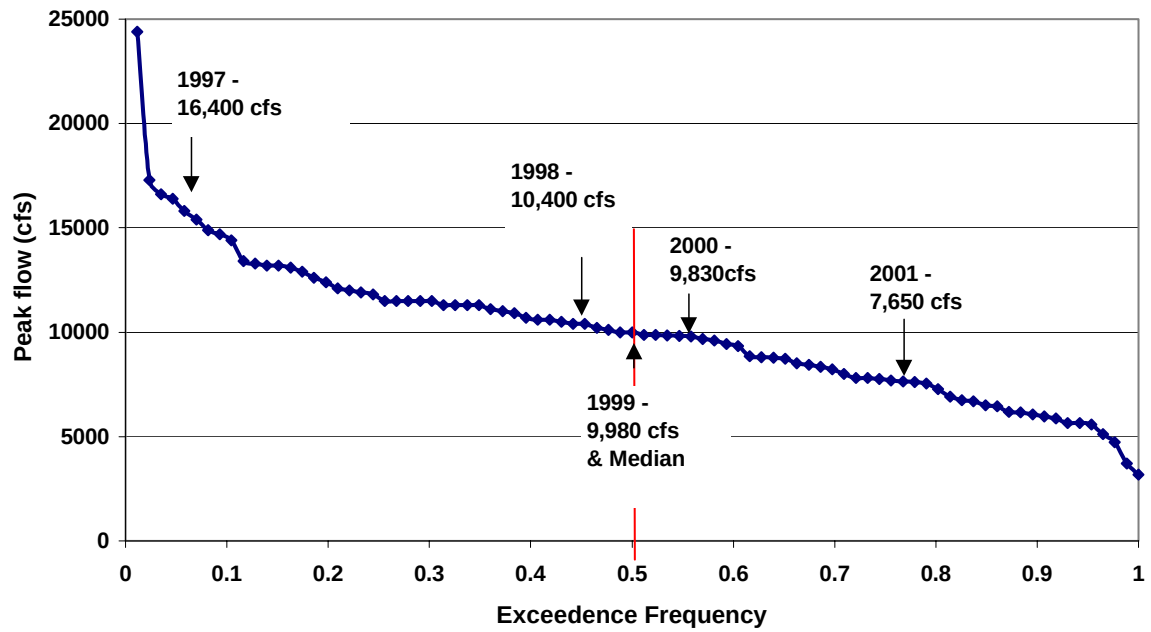


Figure 2. Peak flow during the study period at the Maybell gage with exceedence frequency for the period of record.

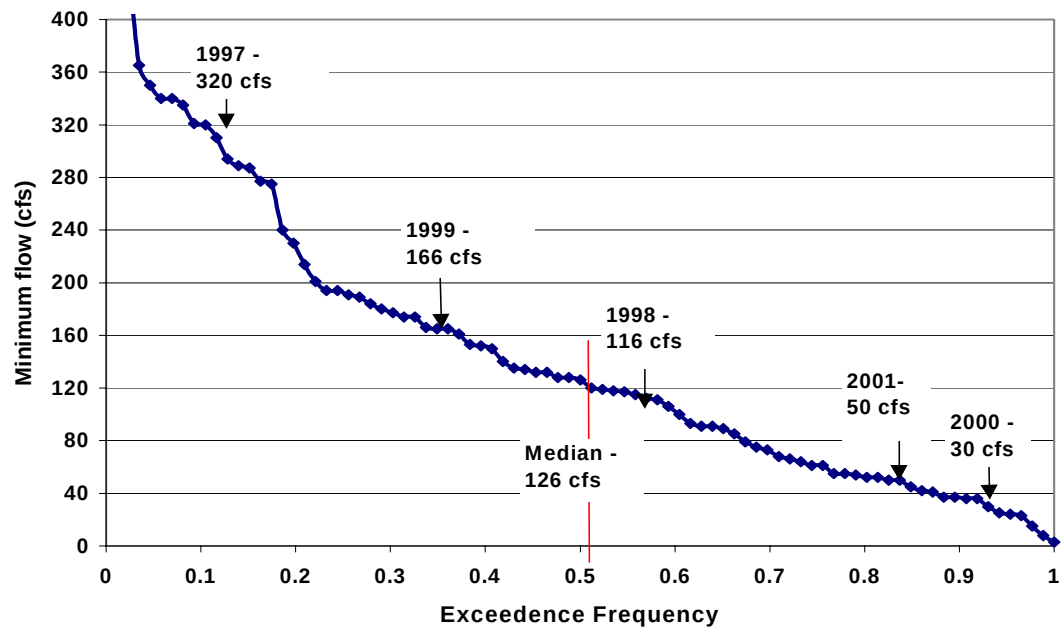


Figure 3. Minimum flows during the study period recorded at the Maybell gage with exceedence frequency for the period of record.

Colorado River – 15-Mile Reach

The 15-Mile Reach of the Colorado River extends from Palisade, Colorado (RM 185), downstream to the confluence of the Gunnison River at about RM 170 (Figure 4). The Colorado River Recovery Program (Osmundson et al. 1995) considers the 15-Mile Reach important for endangered fish recovery. Flows are an issue because of two major upstream diversions that divert flow from the river during the irrigation season (April 1 to November 1). The Government Highline diversion is located in lower Debeque Canyon (RM 193.7) and the Highline canal has a capacity of 1620 cfs. The Grand Valley diversion dam is at RM 185.4. The Grand Valley canal has a capacity of 640 cfs.

A USGS gage, which is located about 0.4 km downstream from the intake for the Grand Valley canal (Figure 4), began operation in 1990. Flows at the Palisade gage are typically 1200 to 1600 cfs less than above the diversion structures in spring and summer. Winter (November to March) flows in the 15-Mile Reach do not appear to create fishery concerns. Flows recorded at the Cameo gage (RM 199.9) appear to be at least at pre-development levels or higher due to senior water right calls at the Shoshone power plant in Glenwood Canyon. Also there can be additional releases for power generation from Green Mountain Reservoir (Per comm. Karen Flogequest (USBR)). Flows recorded at the Palisade gage are usually higher than at Cameo between November and April because Plateau Creek joins the river at RM 193.3. Pitlick (1999) determined bankfull flow to be near 22000 cfs for the 15-Mile Reach.

There are two study sites in the 15-Mile Reach. In 1999, bed topography was mapped from the boat launch at Corn Lake (RM 177.5) downstream to RM 175.3 (Figure 4). This station is named the Corn Lake Site. The Corn Lake site length, which is 3.9 km long and has an average width of 55.2 m at a flow of 1400 cfs, was electro-fished in 1999, 2000 and 2001. The river in this section includes five small backwaters. Flow is generally confined within the main channel as opposed to a braided channel (Figure AF7).

The Clifton Site was added in 2000. This site is about 300 m upstream from the Corn Lake site. The Clifton site is from RM 177.7 to 180.4 and has a total length of 4.2 km. In this section, the river has split flow in two large sections of the channel. There is an old diversion structure located at RM 179.7. The dam backs up water along the north shoreline. There is a large backwater at lower flows. Smaller backwaters like those found in the Corn Lake are uncommon in this site (Figure AF8).

The peak flow for the Palisade gage in 1999 was 12700 cfs on June 10. The peak flow in 2000 was 13,500 cfs on May 31. In 2001 the peak flow was 8,410 cfs on May 21. The median peak flow for the 11-year Palisade gage history is 13,500 cfs indicating that peaks for 1999 and 2000 were near normal. Typically, flows in March are near 2000 cfs, but in some years flows can drop after April 1 due to diversions into the Government Highline and Grand Valley canals. In 1999, flows during the ascending limb (April and May) of the hydrograph flow dropped to 435 cfs on April 15, 1999. That was the minimum flow for the year. The minimum spring flow was 1110 cfs on April 5th, 2000 and 500 cfs on April 17th, 2001.

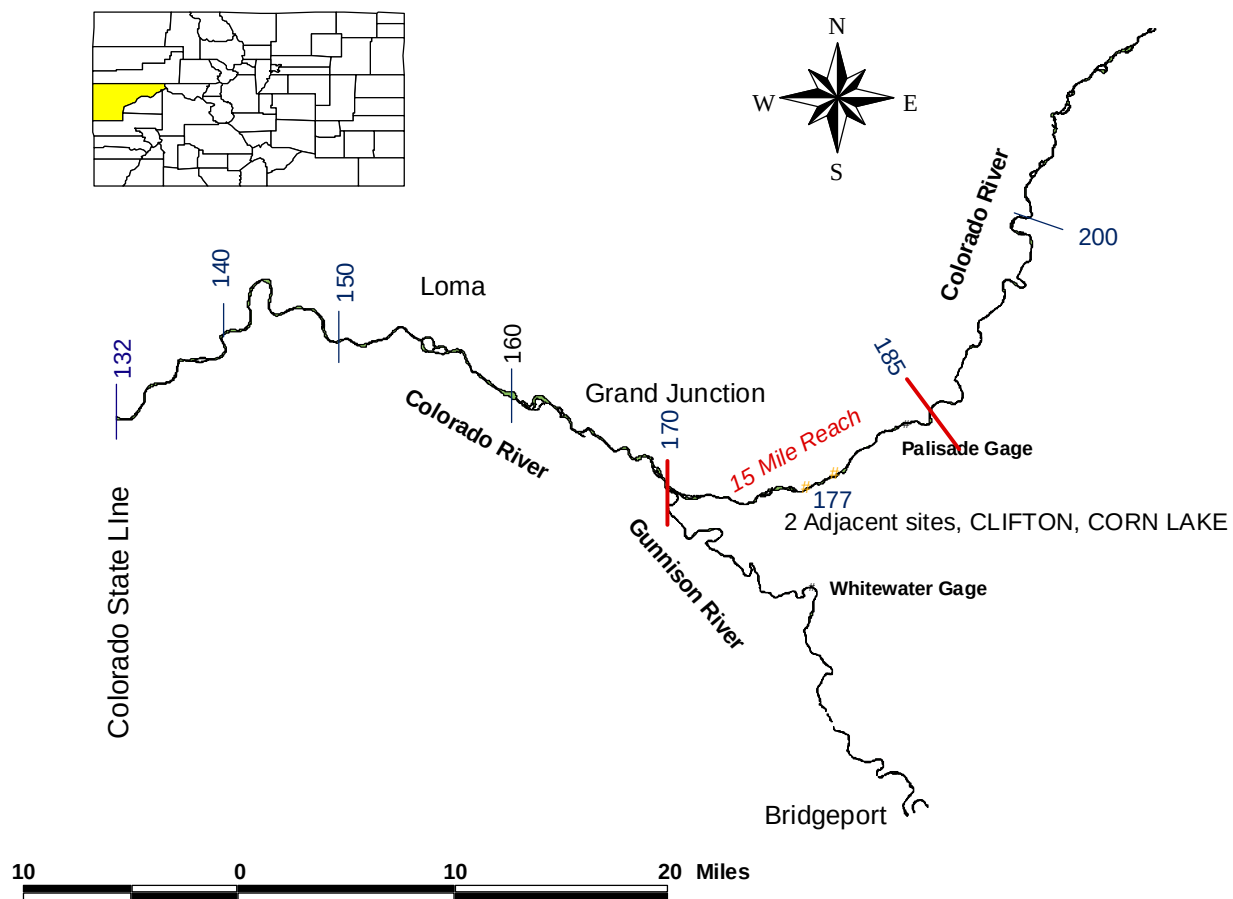


Figure 4. Location of the two study sites in the 15-Mile Reach, Colorado River, Corn Lake and Clifton.

Summer flows were much less in 2000 and 2001 than in 1999. They provided an opportunity to sample the fish population at different flows. Osmundson et al. (1995) made instream flow recommendations for the 15-Mile Reach based on a study of habitat availability for endangered fish. The recommendations from Osmundson et al (1995) were somewhat complex because they wanted to avoid using a single minimum flow. These instream flow recommendations were provided as mean monthly (not mean daily) minimums flows. They varied by season and depending on wet, average and dry flow-year categories determined from historic flow data. The lowest mean monthly flow recommendation was 810 cfs (Table 1), which should only occur at the same frequency as dry years, which was defined as two in ten years. In half the years, the mean monthly minimum flow for August to September should exceed 1630 cfs (Table 1).

Table 1. Recommended mean monthly flows [Osmundson et al (1995)] for the 15-Mile Reach in cubic ft/sec. The exceedence percent indicates frequency that the given flow should be met. For example, during a ten-year period, half the years should exceed a mean flow of 1630 cfs in August, September and October; three of the years should exceed 1240 cfs; and two years should exceed 810 cfs for a mean monthly flow.

Exceedence	July Mean Monthly (cfs)	August Mean Monthly (cfs)	September Mean Monthly (cfs)	October Mean Monthly (cfs)
50% (Wet)	5,370	1,630	1,630	1,630
80% (Normal)	3,150	1,240	1,240	1,240
100% (Dry)	1,480	810	810	810

Since the recommendations from Osmundson et al. (1995) are presented as averages, minimum flows are not the primary consideration. For example, the minimum flow for 2000 was 542 cfs and it was 477 cfs in 2001. The median minimum summer flow for the period of record (11 years) was 588 cfs. Even though flows were less than 810 cfs for 32 days in both 2000 and 2001, these years do not violate Osmundson et al (1995) recommendations. Summer flows in 1999 exceeded the 50% exceedence (wet year) recommendations for all months except July (Table 2) indicating Osmundson considered flows in 1999 optimal. Summer flows in both 2000 and 2001 exceeded the 100% (dry year criteria) in all months except July (Table 2). The federal recommendations, however, will not be “met” if another “dry year” occurs before 2009.

Table 2. Mean monthly and monthly minimum flows recorded at the Palisade gage, 15-Mile Reach, Colorado River for summer months during the three years of the study.

Year		July (cfs)	August (cfs)	September (cfs)	October (cfs)
1999	Mean	4,721	2,221	1,752	1,837
	Minimum	2,500	1,380	1,180	1,430
2000	Mean	1,271	913	986	916
	Minimum	648	581	665	543
2001	Mean	995	1,133	1,014	809
	Minimum	477	686	754	535

Dolores River

The headwaters of the Dolores River lie in the San Juan Mountains. The river flows mostly northward about 200 miles to its confluence with the Colorado River in Utah. The McPhee Dam, which stores water primarily for irrigation, regulates flow for most of the river's course. The McPhee Dam has a capacity of 38 1000 acres/feet and began storing water in 1984. The magnitude of runoff and peak flows are much reduced compared to before 1984. The San Miguel River is of comparable size and joins the Dolores about 117 miles below the McPhee Reservoir. The San Miguel has a relatively unregulated flow.

Access points for boat launches and take-outs were found to be very limited over most of the Dolores River's length. A study site was located in the Big Gypsum Valley, which is 14 river miles downstream from the Slick Rock Bridge and 34 river miles upstream of the Bedrock boat launch (Figure 5). The Dolores River Guidebook (DeVries and Maurer 1977) starts with River Mile (RM) 0.0 at the Bradfield Bridge. The confluence of the Dolores with the Colorado River is RM 171. We used the river guide in reverse RM order to identify landmarks. Beginning at the confluence as River Mile 0.0, the Utah-Colorado State line is RM 22.4, and the **Big Gypsum Study Site is RM 107.1 to 109.9**. The study site starts at the BLM Gypsum Valley Recreation site and ends about 3.0 miles downstream at the 20R (county road) bridge crossing. The study station is about 70 river miles downstream from McPhee Reservoir.

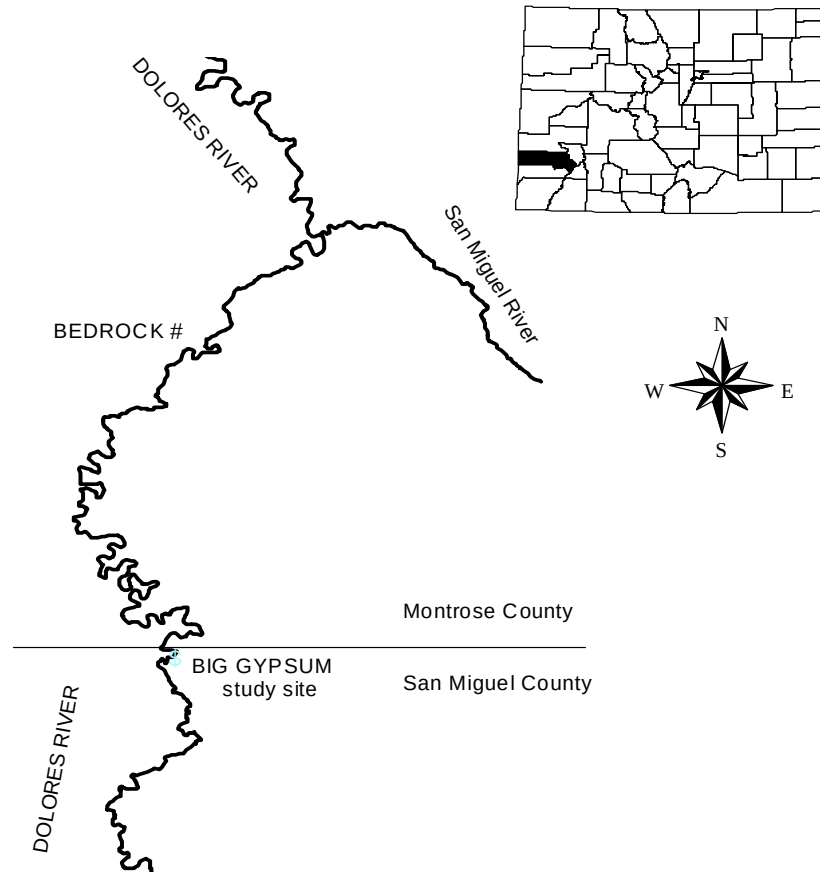


Figure 5. Location of the Big Gypsum (Big Gypsum Valley) study site on the Dolores River.

METHODS

FISH SAMPLING

Fish sampling was performed by electro-shock on the Yampa and Colorado Rivers between 1998 and 2001. Fish were electro-shocked and netted from a 15 ft Achilles raft between 1998 and 2000. A 16-ft Hyside self-bailer raft was equipped for electro-fishing in 2001 using the same Smith-Root electro-fisher, 5000-watt generator and anode array mounted on a forward boom as in the three earlier years. Flows below 120 cfs on the Yampa River were highly problematic for the Achilles boat because it had to be

frequently dragged in shallow reaches. Dragging became the case for the Hyside at flows less than 100 cfs on the Yampa. The boat was maneuvered by either oars or by a battery powered 40-pound thrust trolling motor. Two netters caught as many fish as they could while the shocker was in operation. All fish were measured to the nearest millimeter. Only fish over 150 mm were marked and therefore used for mark and recapture population estimates. Density estimates were made for the each study site on the Yampa, Colorado and Dolores.

The Darroch multiple mark method (Everhart and Youngs 1981) was used to make the population estimate with ninety-five percent confidence intervals. A total fish estimate was made for all species and for each species. Recapture rates generally varied between species and size-groups. For our samplings larger suckers had the highest recapture probabilities. Species with appreciably lower recapture probabilities included catfish, bass, pike and carp (the lower group). The total fish estimate was a blend of recapture probabilities, but should produce reliable comparisons for total fish abundance between years, when species and size composition was consistent. For rare species (pikeminnow, etc) with zero or one recapture in the sample, abundance was estimated by dividing the number in the sample by the mean recapture probability of the lower group.

The z-test with an alpha of 0.05 ($z = 1.96$) was used to test for significant differences in density estimates between years at each station. At stations with three or more years of sampling, the Bonferroni inequality was also used to control the overall significance level (.05) for the simultaneous comparison of all pairs of years (Dr. David Bowden, CSU, pers. communication). At stations with 4 years of data, (Duffy and Sevens) the z value (2.631) corresponds to an alpha of 0.05 divided by six (0.0083).

On the Yampa River, a different mark was used for each run-riffle sequence, which allowed for determining if recaptured fish had moved up, down or had not moved between captures. The dates and the flow for each field trip during the four-year period 1998 to 2001 for Sevens and Duffy are given in Table 3. The Lily Park Site was electro-fished for two years in 2000 and 2001 (Table 3). Flow readings were taken from the Maybell gage. Flows recorded from the Lily Park gage tended to be somewhat higher than Maybell and are included in Table 3 parenthetically.

On the Colorado River, fish in both study sites within the 15-Mile reach were marked to designate the upper, middle and lower sections of the site to give a general idea of movement between passes within the station. A total of eight electro-fishing passes were made at the Corn Lake station in 1999. Four passes were made on the left half and four on right half of the river. The Clifton site was added in 2000 and fish from Clifton were given a unique mark so they could be distinguished from fish marked downstream at the Corn Lake station. The sampling strategy was modified in 2000. The total number of electro-fishing passes was six at both Corn Lake and Clifton. Instead of sampling left and right sides, the river was divided into three longitudinal zones, i.e., right shoreline, left shoreline and mid channel so that fish caught in shallow shoreline habitat were distinguished from the deeper channel habitat. The electro-fishing boat sampled each zone (right and left shoreline and mid channel) twice. In 2001, the same

sampling scheme was used as in 2000 except a seventh pass was performed in the mid-river zone. The additional mid-river pass was found necessary to improve the recapture probabilities for large fish mid-channel. The dates and the mean daily flow (Palisade gage) for that day for the period of sampling is given in Table 3.

The Dolores River was electro-fished in July 2000 and 2001. In both years on the first pass block nets were placed at the downstream end of each run (upstream of riffles). Also, each run was repetitively electro-fished three to five times. Fish from each pass were held in nets, then marked and released into the same run of capture. This process was continued over the entire reach. Block nets were not used on recapture passes. Dates of electro-fishing and flows from the Slick Rock gage is given in Table 3.

CHANNEL TOPOGRAPHY

Global Positioning Systems and Sonar

In 1999 and 2000, bathymetric surveys of the channel were taken of the six study sites using Global Positioning Systems (GPS) and sonar technology. The channel surveying technique previously described in Anderson and Stewart (2000) was performed from a moving boat. A large amount of bathymetry data was gathered in a short amount of time. The GPS system was a Javad Oddyssey L1/L2 RTK GPS with Glonass and Multi-path reduction options turned on. The system had a published vertical accuracy of 15mm +/- 1.5 mm. The sonar unit was an ODOM Hydrographic Systems, Hydrotrac - Single Frequency, Portable Survey Sounder. The sonar unit used a 200kHz frequency with a published accuracy of 1cm +/- 1% of depth and an output resolution of 1cm. The sonar unit pinged and logged ten depth readings per second. The RTK GPS logged one position per second. The RTK GPS system output a NMEA GGA string at a rate of 1Hz while the sonar output text strings indicated depth at a rate of 10Hz. Data from these instruments were sent to a laptop computer and recorded using the COMLOG software from ODOM Hydrographic. Because the RTK GPS and Sonar data were received at different rates, all data entries collected by the COMLOG software were time-tagged to the millisecond using the computer's clock. The depth readings immediately before and after the RTK GPS reading were interpolated by the computer clock time (nearest millisecond) to produce the XYZ coordinates used to map bed topography of the river channel.

Bathymetric data were collected from longitudinal runs and cross-sectional surveys. Special care was taken to ensure that the transducer and GPS antenna were mounted in such a way as to remain nearly vertical during each run.

Table 3. Dates for electro-fishing and flows on the day of the sample.

SEVENS	DATE OF ELECTROFISHING			FLOW IN CFS		
	August	September	October	August	September	October
1998		18, 23, 29	1		222, 189, 163	172
1999	30	1, 14, 16		315	280, 219, 201	
2000		28	4, 9		334	240, 206
2001	24, 30	4		114, 70	64	

DUFFY	DATE OF ELECTROFISHING			FLOW IN CFS		
FULL STAT	August	September	October	August	September	October
1998		16, 22, 24, 30			264, 174, 194, 162	
1999	25	2, 15, 17		237	247, 212, 180	
2000		12, 26	10		69, 518	199
2001	21, 23, 28	6		105, 98, 77	57	

DUFFY	DATE OF ELECTROFISHING			FLOW IN CFS		
DEEP RUN	August	September	October	August	September	October
1998		3, 14, 15			209, 261, 287	
1999	23, 24, 31	7		284, 282, 329	357	
2000		11, 19, 25			79, 57, 632	
2001	20, 27			123, 94		
LILY PARK	DATE OF ELECTROFISHING			FLOW IN CFS		
	August	September	October	August	September	October
2000		13, 27	3, 5		70, 420	260, 215
2001	22, 29	5		91, 85 (151, 110)	61 (96)	

CORN LAKE	DATE OF ELECTROFISHING			FLOW IN CFS		
	Aug.	September	October	Aug.	September	October
1999		28(2x), 29, 30	5, 6, 8, 12		2060, 2000, 1990	1660, 1420, 1740, 1860
2000	15, 17, 22, 24	5, 8		903, 821, 1110, 907	1100, 1090	
2001		16, 19, 24, 26, 28	2, 4		701, 915, 857, 859, 790	715, 689

CLIFTON	DATE OF ELECTROFISHING			FLOW IN CFS		
	August	September	October	August	September	October
2000	16, 18, 23, 25, 30	6		853, 902, 1020, 856, 1290	1080	
2001		20, 21, 25, 27	1, 3, 9		904, 901, 891, 824	735, 684, 543

DOLORES	DATE OF ELECTROFISHING			FLOW IN CFS		
Big Gypsum	July			July		
2000	11, 12, 13, 18, 19, 20, 27			52, 53, 55, 58, 53, 53, 52		
2001	16, 17, 18, 19, 23			66, 68, 68, 53, 50		

Waterline Surveys

One hindrance to using sonar to map the channel bottom involved the equipment's minimum depth limitation. In order for the sonar to get a reading off the bottom of the channel, the transducer had to have at least half a meter of water underneath it. The transducer was located approximately 15cm underwater to allow for the pitch and roll of the boat and to minimize air entrainment under the transducer head. Thus, the minimum depth to gather sonar data was 75 cm.

In areas that were too shallow for data collection by the boat-mounted GPS/sonar method, additional topographic data was collected using RTK GPS in what we referred to as the “walking method”. In this method, the Javad RTK GPS was mounted on a range pole and individual RTK GPS positions were recorded with a Psion data collector running Field Face software. After 2001, a TDS Ranger was used for collecting individual survey points.

Reference Sites

Data collected in the 15-mile reach of the Colorado River were geographically referenced to the Mesa County GPS Survey System (www.co.mesa.co.us, GIS section). Aerial photography of the 15-Mile Reach was purchased from Mesa County to aid in identification of landmarks and waterline boundaries.

The web page of the Mesa County Dept. of Public Works Engineering Division/Survey Section showed the locations of the county markers. Using the latitude and longitude of the brass marker at the intersection of 31 and C Road as a known reference point, we placed secondary rebar survey pins at two places along the 15-Mile Reach. One pin was placed near river mile 175. This pin was used as the reference point for the entire Corn Lake survey. The other pin, located on a bluff just upstream of the 32 Road Bridge on property owned by the Mesa County Highway Department, was used for the Clifton surveys.

On the Yampa and Dolores, initial surveys markers were placed using only uncorrected GPS coordinates. Base pins located by the GPS were then used for all subsequent surveys at each of the sites.

Corn Lake, Colorado River

The Corn Lake site was mapped during a seven-day period beginning June 27th and ending July 7th. Flows were generally between 8,000 and 10,000 cfs. About 38,880 usable bathymetric survey points were collected along a 4.0-km reach. Water edge shots were obtained in October 1999 and July and August, 2000 using the walking method.

Clifton, Colorado River

The Clifton site is located 0.4 km upstream of Corn Lake and is 4.25 kilometer in length. A total of 45,000 usable bathymetric survey points were collected using the GPS/sonar method on May 31, and June 1, 2, 4 and 5, 2000. Flows during this period varied between 10,000 and 13,000 cfs. Waterline/water surface measurements were made by the walking method on August 1, 2 and 3, 2000; January 23, 24, 25 and 26, 2001; and (the final set) June 18,19 and 20, 2001.

Duffy, Yampa River

Bathymetric data was collected along a 2.25 km section of the Yampa River near the Duffy Tunnel using the GPS/sonar method during the period of July 9th to July 11th, 1999. From July 27th through July 29th 1999, the walking method was used to survey waterlines and shallow riffles.

Sevens, Yampa River

On July 12, 1999, bathymetric data were collected using the GPS/sonar technique along a 1.3-km section of the Yampa River at the Sevens study section. The length of this site was believed to be too short given the nature of the associated fish data and the habitats represented in this reach. The Sevens site was enlarged on June 23, 2000, by surveying another 1.3 km immediately upstream and overlapping the site mapped the previous year. These surveys used the same boat and GPS/sonar equipment. To compare bed and water surface elevations between years, three longitudinal profiles were obtained in the 1999 site and water lines and were recorded for the entire 2.6 km station. Collection of bathymetric data was hampered in 2000 by the low and unusually short runoff period.

The base pin established in 1998 was used as the reference position for both the 1999 and 2000 surveys. Shoreline and water surface shots were made using the walking method. Waterline shots for the entire reach were surveyed on October 30 and 31, 2000. Another series of water edge/surface shots were made in June 26 & 27 and July 5 & 6 2001.

Lily Park, Yampa River

Bathymetric data were collected using the GPS/sonar technique along a 3.3-km section of the Yampa River at Lily Park on June 12, 13 and 14, 2000. Collection of bathymetric data was hampered in 2000 by the low and unusually short runoff period. There was a large, wide and shallow riffle near mid-station that could not be surveyed by boat. Therefore, walking method was employed to survey shallow riffles on August 8 and 9 and again on October 19 and 20, 2000. Waterline shots were made on June 27 and 28, 2001, and at a lower flow on July 31 and August 1.

Big Gypsum, Dolores River

Over a three-day period, May 16, 17, and 18, 2000, bathymetric data was collected using the GPS/sonar method along a 3-km section of the Dolores River in the Big Gypsum Valley. As was the case with the Yampa River, the lower than normal runoff flows made data collection using sonar more difficult. Also, certain parts of the river were too shallow for the sonar. Several days were spent in June and July 2000 logging additional points by the walking method. Waterline/water surface shots were made on July 6 and 7, 2000, and on June 13 and 14, 2001.

Velocity Measurements

To calibrate modeled data, it is necessary to have obtained field measurements of depth and velocity at known flows. While depth can be gathered using the same technologies that are used in determining bathymetry, velocity measurements require another set of instruments. Two different technologies were used for measuring velocities in this project.

In 1998, a Marsh McBirney Flo-Mate Portable Flowmeter was used in conjunction with the total station to determine point velocities. The Marsh McBirney had a published accuracy of 1.5cm/s +/- 2 percent. This flowmeter was based on the electrical principle known as Faraday's Law. Here the flow rates were determined by passing a conductive fluid through a magnetic field. A wading rod that held the meter head was placed at a depth chosen to represent average velocity (usually 0.6 of total depth). Locations were recorded by shooting the point with the total station and then recording the average of three 10-second averages. After 1999, locations were recorded by locating the position with the RTK GPS and then recording the velocity of that point.

At high flows it is often not practical to use a wading rod to measure velocities. In May of 2000, a 3MHZ Sontek River Surveyor Acoustic Doppler Profiler (ADP) was used to gather calibration data at the 15-mile reach. The ADP measured the velocity of water using a physical principle called the Doppler shift. This principle stated that if a source of sound was moving relative to the receiver, the frequency of the sound at the receiver was shifted from the transmit frequency. By determining the Doppler shift using three beams, it was possible to determine the relative speed and direction of the flow. Using the Doppler shift from the river bottom to determine the boat speed and direction, we computed absolute velocity and direction. The ADP measured velocities in 15 cm vertical increments down to the river bottom. These velocities were averaged over a specified time interval.

Data Reduction and Preparation

The GPS/sonar technique produced a large number of data in a short amount of time. It generally was not possible to perform any quality control as the data was being collected. Data reduction and quality control were accomplished using an Excel- macro that stripped out non-sensible or incomplete points so only points that met a set of

standard criteria were used in the final survey. The Excel-macro eliminated all non-RTK hits as indicated by the GGA string. This eliminates false spikes in the sonar data sometimes caused by fish or woody debris. Spikes were identified by making a running average of the six nearest sonar pings (three prior and three after). An individual depth reading was marked as “bad” if the difference in between the moving average and the individual ping was greater than 15 cm. If an RTK GPS reading had a “bad” sonar ping recorded directly before or after it, that GPS reading was ignored. For those RTK GPS signals with “good” sonar recordings before and after them, the depth for that GPS position was determined through a linear interpolation of the sonar data based on the time tags. Topographic data were also visually examined by creating Triangular Irregular Networks (TIN).

HYDRAULIC SIMULATION

In the first two years of the project, hydraulic simulation and 2-D flow modeling was contracted with the Earth Resources Department of Colorado State University (CSU). Greg Stewart, a CSU graduate student, collected and input the data to the RMA2-hydraulic model. He performed the analysis during the time period June 1998 to June 2000. Stewart (2000) gives details on hydraulic methods, problems and innovations used for making flow simulations at 15-Mile Reach (Corn Lake) and the Duffy Tunnel site.

Stewart performed most of the installation and operation of technical equipment and data handing for the 2-D modeling. Following his departure, no 2-D modeling was performed until a new contractor was found. In 2002, a new contract was finalized with Utah State University. Dr. Craig Addley, contract administrator for 2-D modeling at Utah State University (USU), supervised modeling for the remaining four sites and some new modeling on Corn Lake. The USU lab used a 2-dimensional, quasi-3-dimensional model developed by Jonathan Nelson of the USGS. The technical description of this model and underlying equations can be found in Nelson (1996), Thompson et al. (1998), Nelson et al. (1995), McLean et al. (1999), Topping et al. (2000).

The 2-D model flow simulations for the Yampa River were meant to cover the range of flow typical in the base flow period, which typically varies between 125 and 200 cfs. Flows simulations at Sevens and Lily Park were produced at 40, 60, 80, 100, 125, 150, 200, 250, 300, 400, 500 and 600 cfs by USU. The Duffy site modeled by Stewart was at flows of 60, 80, 100, 125, 150, 200, 250, 300, 400, 500 and 600 cfs. On the Colorado River base flow was typically much higher than on the Yampa and did not commonly fall below 600 cfs. Stewart ran flow simulations at Corn Lake at 600, 700, 800, 900, 1000, 1200, 1400, 1600, and 1800 cfs. The same flows were modeled for the Clifton site by USU, with additional simulation at flows of 200, 250, 300, 350, 400, 450, 500 and 2000 cfs. Some follow-up modeling was done on the Colorado River so that both sites were modeled down to 100 cfs. Flows on the Dolores River ranged from a low at 10 cfs and a high of 500 cfs.

Site Characterization

Length, mean width and wetted area for each simulated flow were determined for each site using the two-dimensional modeling output data. Station lengths were measured along the channel thalweg. Widths were determined by dividing the wetted channel area at 600cfs (100cfs for Big Gypsum) by the station length. Longitudinal profiles were generated in ArcInfo by sampling channel bathymetry at two-meter intervals along the channel thalweg.

HABITAT QUANTIFICATION

A primary objective of this study was to objectively quantify changes in meso-habitat composition over a range of flows at each site. Meso-habitat is defined at the reach level and includes pools, runs, riffles and rapids. Pools have low velocity, runs have moderate velocity, riffles are swift areas and rapids have the fastest current. For modeling purposes pools were given a velocity of zero to 0.15 m/sec, runs ranged from 0.15 to 0.6 m/sec, riffles had velocity ranging from 0.6 to 1.5 m/sec and rapids had velocities over 1.5 m/sec (Table 4).

Habitat suitability for fish was also a function of depth. Very shallow areas were of high value to small fish, but they had no habitat value to large fish. Pools and runs had five depth categories, riffles had four and two depths categories for rapids (Table 4).

Using only depth and velocity, we defined 16 different non-overlapping meso-habitat types for use in this study. These 16 meso-habitat types provided a general representation of habitat diversity that was inclusive for a fish community composed of a variety of size-classes and species. These 16 meso-habitat types were then mapped using data provided by the 2-D flow models. In each case, solution files (2-D model output) were imported into ArcInfo and then linearly interpolated into 1 x 1-meter grids representing depth and velocity for a given flow. Depth and velocity grids were then sampled to create 1x1-meter meso-habitat grids. The abundance of meso-habitat was determined by counting the number of grids of each meso-habitat type. Surface maps of meso-habitat were created either in ArcView or by importing 2-D plotfiles into SMS (the 2-D modeling package by Boss International).

DEVELOPMENT OF MESO-HABITAT SUITABILITY

Meso-habitat suitability was developed using the fish sampling data. The electro-fishing data was summarized for individual electro-fishing sub-reaches (polygons). The total density and biomass calculated over the entire station did not indicate how fish were distributed within a station, whereas the electro-fishing sub-reaches provided much more detail on fish distribution within the stations. Electro-fishing sub-reaches had the same starting and end locations between passes and years and were digitized on the aerial photos of the study stations using ArcView. The sum of the area and fish from all electro-fishing sub-reaches equaled 100% of the entire station.

Table 4. Depth and velocity criteria used to define meso-habitat types.

	Habitat Types	Depth (m)	Velocity (m/s)
1	Wetted-pool	0.01 – 0.2	< 0.15
2	Shoal-pool	0.2 - 0.5	< 0.15
3	Shallow-pool	0.5 - 1.0	< 0.15
4	Medi-pool	1.0 - 2.0	< 0.15
5	Deep-pool	> 2.0	< 0.15
6	Wetted-run	.01 - 0.2	0.15 - .6
7	Shoal-run	0.2 - 0.5	0.15 - .6
8	Shallow-run	0.5 to 1.0	0.15 - .6
9	Medi-run	1.0 to 2.0	0.15 - .6
10	Deep-run	> 2.0	0.15 - .6
11	Shallow-riffle	< 0.2	0.6 - 1.5
12	Riffle	0.2 to 0.5	0.6 - 1.5
13	Deep-riffle	0.5 to 1.0	0.6 - 1.5
14	Very-deep-riffle	> 1.0	0.6 - 1.5
15	Shallow-rapid	< 0.5	> 1.5
16	Deep-rapid	> 0.5	> 1.5

The meso-habitat suitability analyses used the 2-D hydraulic modeling simulation runs to determine physical attribute metrics for each polygon. This included surface area, mean depth, mean velocity, maximum depth and maximum velocity. Species density and biomass data were calculated based on the percent of fish captured in each sub-reach times the total-reach estimate. Polygons with zero biomass were considered unusable habitat. Polygons that supported high biomass indicated higher habitat quality. Biomass was determined for the flannemouth sucker, bluehead sucker and roundtail chub over 20 cm in length.

The polygon data was used to create four functional meso-habitat types for bluehead and flannemouth suckers. The biomass and mean depth, and mean velocity data was imported into Sigma Plot and then smoothed using a running median function. The result was a regular matrix showing estimated polygon biomass as a function of mean depth and mean velocity. The biomass data were graphed using Sigma Plot software at the scale of 0.1 m, which was used for both axes. For example, bluehead sucker had low biomass in the cell with a depth of 0.6 m and 0.3 m/s, but higher biomass for the cell with 0.6 depth and 0.7 m/s. The data was validated by regression analysis of projected biomass versus observed biomass.

Four levels of suitability were determined from the polygon biomass. Polygons with zero biomass were called Unusable habitat. Unsuitable, Marginal and Optimal were the other meso-habitat types. Each contained roughly about one-third of the total sample size. The lower third or Unsuitable polygons represented about 15% of the total biomass. Marginal represented about 25% Optimal contained about 60% of the total biomass of the total electro-fishing station.

Biomass data for the Colorado River was also examined as a function mean depth and velocity from the electro-fishing done along the shoreline. Shoreline sampling was done in 2000 and 2001 to determine species composition of the shoreline habitats. Shoreline habitats are typically shallow and low velocity and very adult flannemouth and bluehead sucker were captured from shoreline habitats. The shoreline electro-fishing results were similar to the criteria for Unusable habitat determined by the Sigma Polt analysis.

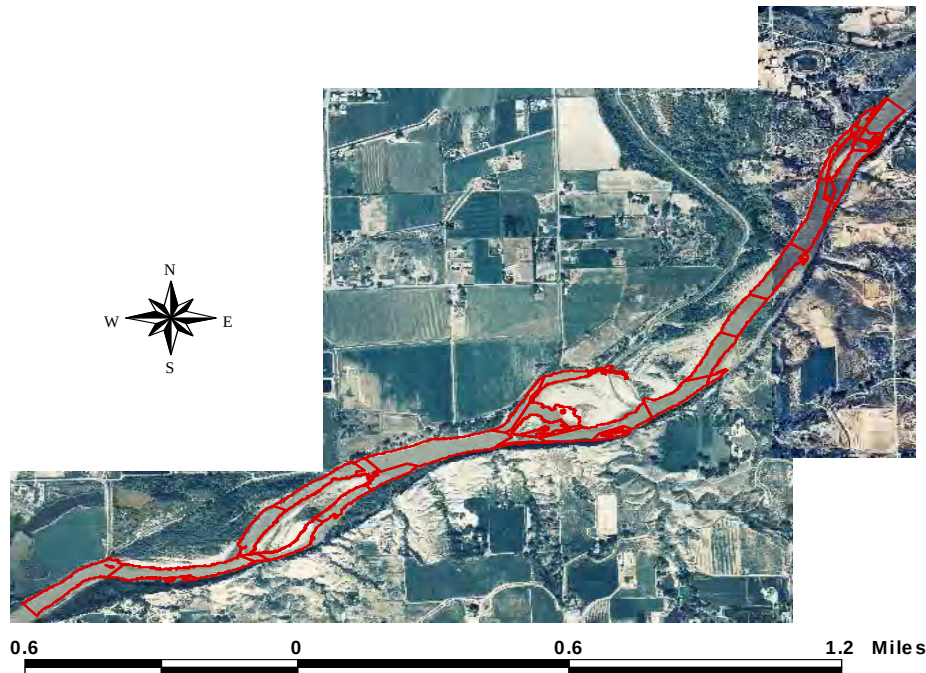


Figure 6. Example of digitized polygons or electro-fishing areas (photo of Clifton site).

DETERMINATION OF HABITAT AVAILABILITY

Once meso-habitat biomass (suitability) criteria for each species of interest were determined, habitat surface area for each of the four meso-habitat types (Unusable, unsuitable, marginal and optimal) was calculated with ArcInfo using the same process as described for the 16-meso habitat types. The surface area of unusable, unsuitable, marginal and optimal habitat was multiplied by the observed mean biomass to give a biomass estimate for both bluehead and flannemouth suckers for each of the simulated flows.

RESULTS

FISHERY QUANTIFICATION

To determine the role flows have on fish community structure it is necessary to quantify both the fishery and habitat availability and then to establish the relationship between habitat and flow. The fishery was characterized by three different attributes for each of the study sites: 1) species composition, 2) size distribution and 3) density and biomass estimation. Since a complete summary of the fish data was in the job progress report, Anderson (2002), not all fish data is presented in this report.

In general, each annual progress report compares species composition, size and density data to the prior year's data. Length frequency histograms for each station sampled in 1998 and 1999 are available in Anderson and Stewart (2000). Histograms for the 2000 sample are given in Anderson and Stewart (2001) and histograms for the 2001 sampling are in Anderson (2002). Length data can also be obtained from the author in spreadsheet format. Seining data is presented in Anderson and Stewart (2000) and Anderson (2002).

Data for the Yampa River was organized by two periods, the first two years (1998 and 1999) had above normal base flows, while base flows during 2000 and 2001 were well below normal. Differences in the fishery between these two periods probably were attributable to differences in base flows. At the Duffy station, fish population sampling was done in a 4.5-mile reach (Long Reach), but only the upper 1.8 miles of the long reach was modeled for habitat composition (habitat reach). The Long Reach fish data was used for making comparisons between years.

Fish Over 15-cm in Length

Native species composition was highly consistent between years at the Sevens station with native fish comprising 73% (four-year mean) of the fish over 15 cm. The four-year mean for flannemouth-sucker composition at Sevens was 49% with a range of 46% to 53%. The four-year mean for bluehead sucker was 19% and it was 4% for roundtail chub (Table 5). Colorado pikeminnow were rare or absent at Sevens for the four-year period. The greatest inconsistency for a native species at Sevens was a drop in bluehead and a small increase in flannemouth composition in the 2001 sample compared against the three prior years (Table 5).

Native fish species were uncommon to rare at Duffy, averaging only 13% of fish over 15 cm for the four years. The data showed a downward trend in native fish at Duffy with highest native fish composition in 1998 (15%) and the lowest in 2001 (10%) (Table 5). Flannemouth suckers were consistently at 5% in the first three years, but were only 2% in 2001. Bluehead suckers comprised about 4% and roundtail chub were 3% over the study period. Colorado pikeminnow were uncommon at Duffy. They comprised between 0.6 to 1.5% of the total catch.

Lily Park had by far the largest sample size for fish over 15 cm, and also the largest variation between years (Table 5). Flannemouth was the most common species found at Lily Park. Its composition was 68% in 2001 and 48% in 2000 (Table 5). The 2001 data was probably a more accurate description of species composition at Lily Park because of the extraordinary number of catfish caught in 2000 decreased the relative abundance of other species that year. Bluehead sucker, roundtail chub and Colorado Pikeminnow composition were similar between years (2001 versus 2000) at Lily park: (9% versus 7%), (0.02% versus 0.03%) and (0.1% versus 0.0%) respectively (Table 5).

Within-station native fish species composition on the Yampa River was quite consistent over the four years of sampling. The differences observed were likely related to either sampling variability between years or difference in flows between years. There were large differences in species composition between stations. Flannemouth composition was about 50% at Sevens, 5% at Duffy and 70% at Lily Park. Bluehead sucker composition was about 20% at Sevens, 4% at Duffy and 8% at Lily Park. Roundtail chub composition was at 4% at Sevens, 3% at Duffy and 0% at Lily Park.

Nonnative fish comprised 85 to 90% of the fish captured at Duffy Tunnel. White sucker and hybridized white sucker averaged 71% of the catch for the first three years (Table 5). The white sucker group dropped to 50% in 2001. At Sevens, the white sucker group was consistent at 15% of the population for the four years. White sucker or hybrids were very rare at Lily Park at 0.03%. Statistics indicate that the white sucker was better suited to conditions upstream of Sevens and native suckers were better competitors at the lower two sites.

There are three non-native predator species in the Yampa River that influence species composition independent of habitat availability. The northern pike was fairly commonly caught during the first two years of sampling (1998 and 1999) at Sevens and Duffy, but were uncommon in the last two years (Table 5). The trend for smallmouth bass was the reverse with the highest composition occurring in the last year, 2001 (Table 5). The most dramatic shift in smallmouth bass was at the Duffy site, from 10% in 2000 to 33% in 2001.

Channel catfish were non-native predators that had a low composition at Sevens (5%) and Duffy (4%). However at Lily Park, channel catfish composition was 40% in 2000 and 18% in 2001 (Table 5). Low flows were identified as problematic for channel catfish migration in 2000, inflating their numbers relative to normal flow years. A composition of 18% for catfish was a more likely representation for this species. In 2000, smallmouth bass comprised only 0.8% of the fish over 15 cm, but in 2001 smallmouth bass were 5 percent (Table 5).

Table 5. Species composition for fish over 15 cm from all study sites. Composition is from total number of fish measured.

YAMPA RIVER	SEVENS	SEVENS	SEVENS	SEVENS	MEAN	MEAN
Species	1998	1999	2000	2001	98,99,00	4 years
Flannemouth Sucker	48%	46%	50%	53%	48%	49%
Bluehead Sucker	23%	18%	22%	13%	21%	19%
Roundtail Chub	5%	4%	4%	3%	4%	4%
Colo. Pikeminnow	0.20%	0.20%	0.25%	0.00%	0%	0.2%
White S. + Crosses	11%	15%	17%	16%	14%	15%
Channel Catfish	7%	7%	2%	5%	5%	5%
Carp	4%	5%	4%	4%	4%	4%
Smallmouth Bass	1.0%	2.5%	0.5%	5.0%	1%	2%
Northern Pike	1.3%	1.9%	0.2%	0.3%	1%	1%
Sample size	1391	1026	807	676		
YAMPA –REACH	DUFFY	DUFFY	DUFFY	DUFFY	MEAN	MEAN
Species	1998	1999	2000	2001	98,99,00	4 years
Flannemouth Sucker	5%	5%	5%	2%	5%	4%
Bluehead Sucker	4%	6%	4%	4%	5%	4%
Roundtail Chub	3%	3%	4%	3%	3%	3%
Colo. Pikeminnow	1.5%	0.6%	0.8%	0.6%	1%	1%
White S. + Crosses	69%	72%	73%	50%	71%	66%
Channel Catfish	3%	4%	3%	4%	3%	4%
Carp	3%	1%	1%	2%	2%	2%
Smallmouth Bass	8%	6%	10%	33%	8%	14%
Northern Pike	2.8%	2.3%	0.9%	1.1%	2%	2%
Sample size	1653	2092	1294	856		
YAMPA RIVER			Lily Park	Lily Park		MEAN
Species			2000	2001		2 years
Flannemouth Sucker			48%	68%		58%
Bluehead Sucker			9%	7%		8%
Roundtail Chub			0.02%	0.03%		0.03%
Colo. Pikeminnow			0.1%	0.0%		0.1%
White S. + Crosses			0.3%	0.2%		0.3%
Channel Catfish			40%	18%		29%
Carp			2.1%	2.1%		2.1%
Smallmouth Bass			0.8%	5%		3.0%
Northern Pike			0.2%	0.2%		0.2%
Sample size			4058	2989		
COLORADO RIVER		CORN L.	CORN L.	CORN L.		MEAN
Species		1999	2000	2001		3 years
Flannemouth Sucker		38%	31%	40%		36%
Bluehead Sucker		35%	36%	38%		36%
Roundtail Chub		3%	4%	3%		3%
Colo. Pikeminnow		0.10%	0.04%	0.03%		0.06%

Razorback Sucker		0.20%	0.30%	0.06%		0.19%
White S. + Crosses		6%	5%	6%		6%
Channel Catfish		4%	6%	5%		5%
Carp		11%	14%	6%		11%
Sunfish (all species)		0.9%	1.5%	0.7%		1.0%
Trout (all species)		0.0%	0.1%	1.4%		0.5%
Bullhead		1.3%	0.6%			1.0%
Sample size		3499	2784	3463		
COLORADO RIVER		CLIFTON	CLIFTON	CLIFTON	MEAN	MEAN
Species		1999	2000	2001	2 Years	3 years
Flannemouth Sucker		33%	33%	42%	37%	36%
Bluehead Sucker		23%	41%	27%	34%	30%
Roundtail Chub		7%	5%	6%	6%	6%
Colo. Pikeminnow		0.50%	0.03%	0.09%	0.06%	0.21%
Razorback Sucker				0.04%	0.04%	0.04%
White S. + Crosses		5%	4%	4%	4%	4%
Channel Catfish		14%	5%	6%	5%	8%
Carp		16%	12%	14%	13%	14%
Sunfish (all species)		0.9%	1.2%	1.1%	1.2%	1.1%
Trout (all species)		0.5%	0.1%	0.2%	0.2%	0.3%
Bullhead		0.5%	0.2%	0.4%	0.3%	0.4%
Sample size		575	3276	4485		
DOLORES RIVER			BIG GYP	BIG GYP	MEAN	MEAN
Species			2000	2001		2 years
Flannemouth Sucker			16.0%	57.5%		36.8%
Bluehead Sucker			2.2%	5.8%		4.0%
Roundtail Chub			54.9%	24.5%		39.7%
Channel Catfish			15.8%	8.3%		12.1%
Carp			3.4%	1.7%		2.6%
Green Sunfish			2.0%	1.4%		1.7%
Bullhead			5.2%	0.6%		2.9%
Sample size			501	636		

Native species composition was also consistent between years for the Colorado River stations. At Corn Lake, native fish comprised 76% (three-year mean) of the fish over 15 cm with an even split of 36% for flannemouth and bluehead suckers (Table 5). The three-year mean for roundtail chub was 3% (Table 5). Colorado pikeminnow were very rare at 0.06 percent. All razorback sucker caught were stocked fish. The greatest inconsistency for a native species at Corn Lake was for flannemouth sucker composition in 2000. This was probably resulted from a different sampling effort that year.

In 1999, a two-pass effort was made at the Clifton station to see if marked fish from Corn Lake would be recaptured outside the site (Anderson and Stewart 2000). This data allowed for three years of species composition data to be collected on the Clifton reach. At Clifton, native fish comprised 76% (two-year mean) of the catch.

Flannemouth composition averaged 36%, bluehead 30%, and roundtail chub 6 percent. Colorado pikeminnows were very rare at 0.2 percent.

Both Colorado River sites had 76% native fish and 36% flannemouths. Clifton had a lower abundance of bluehead, but higher numbers of roundtail chub, suggesting subtle habitat differences for these species between these two sites.

Relative abundance of flannemouths, blueheads and roundtail chub remained stable over three years at the two Colorado River sites. Minor fluctuations in community composition between years were well within the range of sampling error. They, therefore, probably do not reflect any real change in species composition. Sampling efficiency was influenced by a number of factors including flow, water clarity, effort and ability of netters. Flow conditions during sampling were fairly similar in 2000 and 2001, but were much higher in 1999. In 2000, sampling after thunderstorms or during periods of reduced water clarity was more common. There were fewer passes made in 2000 than in 1999 and 2001. Also, shoreline habitats received proportionally more effort in 2000 than in the other years.

Nonnative fish comprised 24% of the fish community over 15 cm at the two sites in the 15-Mile Reach. Common carp was the most frequently occurring nonnative species collected at both sites. The three-year mean for carp was 11% at the Corn Lake site and 14% at Clifton (Table 5). Carp displayed the most movement between stations based on recapture locations. Carp composition was much higher in the Colorado River than in the Yampa River, suggesting the Colorado River has better carp habitat.

The mean composition of white suckers, plus white sucker hybrids with flannemouth and bluehead suckers, was 6% at Corn Lake and 4% at Clifton in 2001 (Table 5). The white sucker catch was much higher in backwater habitats than in the main channel. On the Yampa River, white sucker was a main channel species in the Duffy and Sevens sites while white sucker were very rare at Lily Park (0.3%). The other common nonnative fish in the 15-Mile Reach was the channel catfish, which was 5% at both stations. Unlike the Yampa River, there appears to be local reproduction of catfish in the 15-Mile Reach.

The Dolores River site at Big Gypsum was sampled in 2000 and 2001. Species composition differed greatly between the two years. In 2000, flannemouth sucker represented 16% of fish over 15 cm. That rose to 58% in 2001 (Table 5). Roundtail chub represented 55% in 2000 and 25% in 2001 while bluehead sucker was 2% of the sample in 2000 and 6% in 2001. Native fish comprised 73% of the fish population in 2000 and 86% in the 2001 sample. The most common non-native fish in 2000 was channel catfish at 16%, but represented 8% in 2001.

The Big Gypsum stations had the highest composition of roundtail chub of all sites and the highest composition of native fish in general. However, there was instability in species composition between years at Big Gypsum. This instability was probably related to the much different flow conditions between years, with lower flows in 2001.

Even though native fish composition was high at the Big Gypsum site, other fishery factors indicate that the habitat conditions at this site were severely degraded.

Fish Less Than 15 cm in Length

The speckled dace and the mottled sculpin, two small-bodied native species that are associated with riffles or swift current habitats, were commonly observed at the Duffy station in 1998 (13%; 19%) and 1999 (8%; 27%). Conversely, both species were very rare in 2000 (1.2%; 5%) and 2001 (0.2%; 0.8%). The reduced number coincided with reduced flows in 2000 and 2001.

A large increase in young-of-year (YOY) smallmouth bass composition was observed in 2000 and 2001 (lower flow years). Species composition for YOY smallmouth bass at the Duffy station was 45% in 1998 and 42% in 1999. In these higher flow years, most YOY smallmouth bass were collected from shoreline habitats. YOY smallmouth bass composition was 84% in 2000 and 98% in 2001. Also during those years, YOY smallmouth bass occupied riffles as well as the shoreline habitats. The shift from speckled dace to YOY smallmouth bass in riffle habitats was also observed at Sevens in 2000 and 2001. This suggested the shift occurred river-wide.

Shoreline seining done in 1999 and 2001 gave a more quantitative count of fish less than 15 cm. The number of speckled dace collected by seine in 1999 at Duffy was 538 for 24% of the total, whereas seining in 2001 collected zero speckled dace (Table 6). The number of white suckers collected in seines in 1999 was 497 (22% of the total catch), but only 11 (1%) white suckers were caught in 2001. Smallmouth bass numbers were 35 (1.5%) in 1999 and 540 (67%) in 2001. Increases in YOY smallmouth bass during 2001 appeared to be related to the low flow conditions during that year as compared to higher base-flow conditions in 1999.

Low densities or abundance of speckled dace and mottled sculpin were also observed at Sevens. Speckled dace species composition (n) in 1998, 1999, 2000 and 2001 was 38% (123), 13% (10), 2% (11) and 2% (3) respectively, and for mottled sculpin, 5% (16), 0%, 0%, and 0% respectively (Table 6).

Speckled dace appeared to be very common during sampling on the Colorado River. Since other agencies were doing concurrent fish sampling in the 15-Mile Reach, no special effort was made to sample small-bodied fish. Miller et al (2003) made a density estimate of 2.36 dace per square meter for riffles and 0.50 in runs. Based on habitat availability, Miller et al. (2003) estimated speckled dace at 34,000 dace per km in the 15-Mile Reach.

In addition, no special effort was made to quantify non-native cyprinids (NNC; red shiner, sand shiner and fathead minnows) since this fish group was not involved in instream flow recommendations. These species were very abundant in shoreline and backwater habitats (Valdez 1999, Bundy and Bestgen et al. 1999, and McAda et al. 1997, and other annual ISMP reports).

Table 6. Species composition from seine hauls at the Sevens and Duffy sites in 1999 and 2001, Yampa River.

STATION	SEVENS	SEVENS	DUFFY	DUFFY
YEAR	1999	2001	1999	2001
TOTAL (n)	2165	2026	2272	803
	% (n)	% (n)	% (n)	% (n)
Flannemouth sucker	1.1 (23)	5.4 (109)	1.0 (23)	0
Roundtail Chub	1.4 (34)	2.2 (45)	34 (733)	1.4 (11)
Speckled Dace	3.8 (83)	1.9 (39)	24 (538)	0
Sand Shiner	57 (1241)	82 (1662)	13.9 (315)	29.5 (237)
White Sucker, & crosses	27 (588)	4.3 (88)	21.9 (497)	1.2 (11)
Smallmouth bass	0.4 (9)	1.5 (30)	2.5 (57)	67 (540)
Fathead minnow	3.6 (77)	2.5 (50)	0.4 (10)	0.1 (1)
Carp	4.3 (93)	0	1.5 (35)	0.2 (2)
Stickleback	0.7 (16)	0.1 (3)	0.4 (9)	0
Redside shiner	0.05 (1)	0	0.04 (1)	0
Plains Killifish	0.05 (1)	0	0	0

All small green sunfish sighted were netted, and most were captured in backwater habitats. Removal of sunfish species was attempted in 2001 and 2000, but not in 1999, since the Recovery Program was conducting centrarchid removal in some of the same backwaters during that time. In general, green sunfish numbers were higher during years of lower flow (2001) than during the high year (1999). However, the magnitude of flows observed during the study period did not appear likely to give sunfish species a competitive advantage in the Colorado River as was observed on the Yampa River.

YOY and juvenile flannemouth and bluehead suckers and roundtail chubs were collected in the Colorado River in all years indicating that suitable habitat was available and that predation was not problematic for younger life stages. In contrast, YOY and juvenile flannemouth and bluehead suckers were very rare on the Yampa River.

The sample size for fish less than 15 cm was highest in 2001. This could reflect increased sampling efficiency in backwaters and shorelines or an actual increase in small fish numbers. Small fish numbers can increase during low flow conditions because of increased habitat and water temperatures. A longer growing season and more primary productivity is usually associated with higher water temperatures. Flow conditions in both 2000 and 2001 may have been more conducive for small fish than in 1999.

Table 7. Species composition for fish greater and less than 15 cm at the Big Gypsum site on the Dolores River, July 2001.

	Big Gypsum 2001	Big Gypsum 2000	Big Gypsum 2001	Big Gypsum 2000
Species	>15 cm	>15 cm	<15 cm	<15 cm
Flannemouth Sucker	57.5%	16.0%	9.9%	5.2%
Bluehead Sucker	5.8%	2.2%	14.2%	0.0%
Roundtail Chub	24.5%	54.9%	16.5%	48.0%
Channel Catfish	8.3%	15.8%	0.4%	1.4%
Carp	1.7%	3.4%	0.0%	0.2%
Green Sunfish	1.4%	2.0%	1.5%	5.7%
Pumpkinseed	0.0%		0.5%	
Brown trout		0.6%		
Black Bullhead	0.6%	5.2%	0.5%	0.2%
Speckled Dace	0.0%		17.5%	33.8%
Mottled Sculpin				
Red Shiner	0.0%		36.3%	5.2%
Sand Shiner	0.0%		2.3%	0.2%
Fathead minnow	0.0%		0.5%	0.2%
Native species	87.9%	73.1%	58.1%	87.0%
Sample size	636	501	2159	577

The number of fish less than 15 cm was much higher in 2001 (2,159) than in 2000 (577) in the Dolores River (Table 7). Many more red shiners were observed in 2001. This was the most common species at 36% in the less than 15-cm group. Speckled dace was the next most common fish under 15 cm at 18 percent. Young flannemouth suckers, bluehead suckers and roundtail chub were also common in the small fish group at 10%, 14% and 17% respectively in 2001. Native fish comprised 58% of the less than 15-cm fish sample in 2001 compared to 87% in 2000 (Table 7).

Size Structure for Native Fish

Length frequency histograms for each station sampled in 1998 and 1999 are available in Anderson and Stewart (2000). Length frequency histograms for the 2000 sample are given in Anderson and Stewart (2001) and histograms for the 2001 sample are found in Anderson (2002). There are no length frequency histograms given in this report, but summaries presented herein are based on data from the progress reports. Readers can refer to these progress reports for comparison between stations and between years. Some histograms from 2000 at Sevens are incorrect (bluehead, flannemouth and catfish) or not included (Lily Park, smallmouth bass). Corrected histograms are found in Anderson (2002).

The Yampa site Sevens had a decrease in mean size of the bluehead sucker in 2000 and 2001 compared to 1998 and 1999 (higher flow years). Both mean length and sample size were smallest in 2001 at Sevens (Table 8). The 30.0-cm mean length was the smallest mean size for any site on the Yampa and Colorado. Duffy was the only site where mean lengths were not significantly different between years (Table 8). Bluehead suckers under 34 cm were rare at Duffy, likely due to predation. The bluehead's mean length of 36 to 38 cm was the highest for any site on the Yampa or Colorado River (Table 8). At Lily Park, bluehead under 28 cm were rare in both years and the means were similar (Table 8).

The length frequency for bluehead suckers on the Colorado River contained juvenile and adult-size fish. Mean length of the bluehead sucker was 33 to 35 cm (Table 8).

Mean lengths of the bluehead sucker on the Dolores River were noticeably different from all other sites with no collected bluehead sucker being over 28 cm in either sampling year. A very high number of yearling (325) bluehead sucker were caught at Big Gypsum in 2001, but no fish in that size-group was collected in 2000 (Table 8). About the same number of fish between 19 cm and 28 cm were collected in both years (11 in 2000, 18 in 2001).

Table 8. Mean lengths of bluehead sucker captured during the study period (1998 to 2001), Yampa, Colorado and Dolores Rivers.

	1998,a	1999,b	2000,c	2001,d
	Mean length of bluehead sucker in cm			
Sevens	33.5,cd	33.6,cd	31.3,abd	30.0,abc
Duffy	36.5	37.9	37.6	36.2
Lily Park			34.4,d	33.5,c
Corn Lake		36.5,cd	33.3,bd	34.8,bc
Clifton			31.8,d	33.5,c
Dolores			23.6	12.1
	Total number in sample - Number less than 15 cm			
Sevens	314 - 0	187 - 0	180 - 0	89 - 0
Duffy	56 - 0	102 - 0	45 - 0	41 - 3
Lily Park			347 - 3	212 - 0
Corn Lake		1212 - 3	1010 - 16	1283 - 31
Clifton			1374 - 51	1228 - 35
Dolores			11 - 0	343 - 308

*a, b, c, d following a mean length indicates significant difference (2 tail test) at $\alpha=0.5$.

The length frequency histograms and mean sizes were very similar for the flannelmouth sucker for the first three years at Sevens. But, their size decreased in 2001 compared to prior years. The mean length (43.8 cm) was significantly lower (Table 9).

Because the number of flannelmouth was low at Duffy in 2001 ($n = 17$) (Figure A8), the 2001 mean lengths (47.5 cm) were not significantly different from prior years (Table 9). The mean lengths of flannelmouth at Sevens (46 cm) and Duffy (49 cm) (Table 9) were high because there were no juvenile fish at these sites. This was most likely a result of predation. At Lily Park, mean length was significantly less in 2001 (38.4 cm) than in 2000 (41.5 cm) (Table 9) due to more fish less than 29 cm in 2001 (153) than in 2000 (4).

At Corn Lake, mean length of the flannelmouth was 39 to 41 cm (Table 9). The size structure of flannelmouth in the Colorado River ranged from 7 to 55 cm with modes representing all age groups. This suggested abundant habitat and no predation or competition.

On the Dolores River only three adult flannelmouth sucker were collected in 2001. The low mean length was representative of a population that had either poor habitat or limited forage availability for adult size fish. There was apparently very good reproductive success among flannelmouth in the Dolores River, since the vast majority of fish were between 9 and 19 cm in 2001. In 2000, most flannelmouth were between 16 to 26 cm in 2000.

Size structures of roundtail chub at Sevens and Duffy in 2001 were very similar (not significantly different) to prior years, but sample sizes were less at both sites (Table 10). The small decrease in mean lengths in 2001 (Table 10) was due to only one or two additional small fish in the sample, not a shift in size distribution. The high mean lengths at Sevens (38 to 40 cm) and at Duffy (43 to 44 cm) for the study period were due to few yearling and juvenile fish in the sample. Only one chub was collected at Lily Park in 2000 and in 2001. On the Colorado River, both large and small roundtail chub were present in 2000 and again in 2001 at Corn Lake and at Clifton. Mean lengths were not significantly different between Corn Lake (23.5, 20.9 cm) and Clifton (25.0, 22.1 cm) in the same year, but the differences were significant between 2000 and 2001 at both sites. On the Dolores River, roundtail chub ranged in size from two cm to 27 cm with only one large chub at 40 cm.

The length frequency data contained a lot of information about these fish populations. When smaller fish appeared as modes on the graph it was an indication of successful reproduction and survival of younger year-classes. On the Yampa River at Sevens and Duffy very few fish were collected in the size range of 15 to 35 cm, but fish larger than 40 cm were common. This indicates that predators in the Yampa River, primarily northern pike, have had a heavy impact on 15 to 35 cm fish. On the Colorado River, lengths were evenly distributed and showed the presence of multiple year-classes. The lack of predation in the Colorado River apparently allowed a natural length distribution to develop that was based on limits set by habitat availability.

Table 9. Mean lengths of flannelmouths captured during the study period (1998 to 2001), Yampa, Colorado and Dolores Rivers.

	1998a	1999b	2000c	2001d
	Mean length of flannelmouth sucker in cm			
Sevens	45.7,d	46.5,d	45.8,d	43.8,abc
Duffy	48.9	49.0	49.8	47.5
Lily Park			41.5,d	38.4,c
Corn Lake		41.2,cd	38.9,bd	40.6,bc
Clifton			38.3	38.8
Dolores			18.8d	14.2c
	Total number in sample - Number less than 15 cm			
Sevens	668 – 0	476 – 0	404 – 1	359 – 0
Duffy	90 – 0	79 – 0	65 – 0	17 – 0
Lily Park			1,935 – 0	2,022 – 0
Corn Lake		1,384 – 46	928 – 65	1,495 – 39
Clifton			1,106 – 55	1,934 – 53
Dolores			110 – 30	580 – 271

- a, b, c, d following a mean length indicates significant difference (2 tail test) at @=0.5 for those years.

Table 10. Mean lengths of roundtail chub captured during the study period (1998 to 2001), Yampa, Colorado and Dolores Rivers.

	1998a	1999b	2000c	2001d
	Mean length of roundtail chub in cm			
Sevens	39.0	40.0,d	39.2	37.9,b
Duffy	43.5	44.5	44.2	43.4
Lily Park			40.3	18.0
Corn Lake		23.3,d	23.5,d	20.9,bc
Clifton*		28.9	25.0,d	22.1,c
Dolores			14.1,d	10.9,c
	Total number in sample - Number less than 15 cm			
Sevens	73 – 0	39 – 0	31 – 0	23 – 0
Duffy	55 – 1	44 – 0	46 – 0	27 – 1
Lily Park			1 – 0	1 – 0
Corn Lake		188 – 78	145 – 26	193 – 89
Clifton*		47 – 4	196 – 29	446 – 186
Dolores			275 – 277	145 – 367

* a, b, c, d following a mean length indicates significant difference (2 tail test) at @=0.5 for those years.

The Dolores River displayed yet a third pattern in length frequency. In the Dolores River, small fish (<15 cm) were abundant, but large fish (> 25 cm) were very rare. The Dolores does not have obvious predation impacts. The channel catfish was the only non-native predator species and typically small sized fish disappeared by predation. The lack of large fish was likely a function of a lack of habitat. The Dolores River

appeared to be a model of small fish having the advantage in the shallower pools and runs of this site. The Colorado River was a model of larger fish occurring in big the deeper and faster habitats typical of this river.

Density and Biomass Estimation

The biomass estimate included both size and density and was the best measurement of fish productivity for a river reach. Species composition and length frequency analysis provided necessary information about factors that may be influencing the biomass estimate. It was assumed that the carrying capacity (potential biomass) of a community and for individual species was set by a combination of habitat and forage availability. Other factors that reduced a particular species biomass below the habitat potential included predation, competition and hybridization as were described above for each site. Native fish biomass on the Colorado, Dolores Rivers and the Lily Park (Yampa River) was likely a good estimated of carrying capacity. The Sevens site was found to be less impacted by predation and hybridization than Duffy. The other primary variable in the carrying capacity equation was forage availability. Riffles were the most productive habitats for aquatic invertebrate production. Therefore, riffle habitat availability may also have influenced fish biomass. Given these background variables, biomass (fish productivity) at each site was used to indicate habitat potential for native fish between years and between sites.

In 1998 and 1999 at the **Duffy** Reach, total fish density and biomass estimates were similar at 378 and 403 fish/km and 73 and 65 kg/ha respectively (Table 11). Density estimates were not significantly different ($\alpha = .05$) for 1998 and 1999. The 2000 density estimate of 316 was significantly lower ($\alpha = .05$) than prior years. The total biomass estimate at Duffy in 2000 was 49 kg/ha. It was 42 kg/ha in 2001. Density and biomass estimates were down for all species except smallmouth bass in 2000 and 2001 (A-Table 1 and 2). The base flows during 2000 and 2001 were much less than in 1998 and 1999. Reduced fish biomass during the low flow years was also found at the other Yampa River sites. This was consistent with reduced carrying capacity in those years.

The density estimate for both white sucker and hybrids in 2001 was the lowest of the study period and was significantly different from the three prior years (A-Table 1). At **Duffy** large-bodied species decreased in density in 2001 compared to years with higher base flows. The only species to increase in density and biomass in 2001 was the smallmouth bass, a smaller bodied species that can utilize shallow habitats.

Total density estimates at **Sevens** were similar in 1998 (1,147 km) and 1999 (1,115/km) (Table 11). Biomass was 183 and 162 kg/ha in those years (Table 12). The density estimates dropped in 2000 (778/km) and 2001 (653/km). The biomass estimate in 2000 was 102 kg/ha. It was 79 kg/ha in 2001 (Table 12). The lower biomass was again associated in the years with the lower base flows, an indication of reduced carrying capacity at the flows of those years. Also consistent with Duffy is the lower estimate for

northern pike in 2000 and 2001. That suggests the risk of predation by this species was higher in 1998 and 1999.

Flannemouths were the most common fish greater than 15 cm collected in all four years at **Sevens**. This species had the highest density estimates except in 2000. Flannemouth sucker estimates were similar for 1998 and 1999, and similar for 2000 and 2001, but the periods differed from each other. The lowest numbers of bluehead were caught in 2001, but the estimate was not significantly different than in other years because of the lower number of recaptures (higher variance). The electro-fishing effort was roughly equal between years at Sevens and, based on effort, it appeared bluehead suckers were more scarce in 2001. The same applied to roundtail chub. Sample size was small for roundtail chub in all years and recapture rates were not high enough to produce tight confidence intervals. In 2001, fewer fish were caught given a similar sampling effort, but it was not statistically significant. The fact that total fish and native sucker density was less in 2000 and 2001 at both Sevens and Duffy indicates a common cause (likely flows) at both locations.

Lily Park was added to the study in 2000 so data is not available for the higher base flow years. The two years (2000 and 2001) of data were strikingly different. Anderson (2002) explained that channel catfish and flannemouth sucker estimates were highly biased in 2000 as a result of very low summer flows and that the 2001 data was better for comparing density and biomass with other stations.

In 2001, **Lily Park** had by far the highest total fish density of 3,168 fish/km (Table 11) at the three Yampa Sites. Total biomass (kg/ha) at Lily Park was 3.7 times higher than at **Sevens** and 7.0 times higher than at **Duffy** (Table 12). These data strongly indicated that Lily Park had higher total productivity than the upstream sites. Lily Park was only ten river miles downstream of Sevens, suggesting similar temperature and water quality attributes. Also, there appeared to be a larger predator population of northern pike and smallmouth bass at Lily Park (Table 11). Most of the differences in fish density between Lily Park and Sevens were likely habitat related.

Flannemouth biomass at **Lily Park** was 3.6 times higher and bluehead sucker density was 3.9 times higher than **Sevens**. The 37% decrease in bluehead density at **Lily Park** between 2000 and 2001 indicated reduced abundance between years. Roundtail chub density for fish over 15 cm was highest at Sevens. The near zero chub density at Lily Park (Table 11) indicated a lack of habitat there. It seemed more likely spawning or YOY habitat was missing for chub at Lily Park. Hybridization at **Duffy** did not allow for comparing native sucker density and biomass to other sites. Also predation at Duffy may have been reducing the density and biomass estimates below the potential for this site.

In spite of the problems identified with the 2000 **Lily Park** density data, the sampling effort was beneficial for documenting habitat used at this location. Many flannemouths were collected from deep eddies and pools on September 13, 2000, at 114 cfs (Lily Park gage). But, on subsequent passes at higher flows (September 27, October 3 and 5) flannemouth were not captured from those backwaters, but in runs with suitable

depths. These observations directly showed that flannelmouths occupied habitats at low flows (100 cfs) that were not used at higher flows (over 120 cfs). This

Table 11. Density and biomass estimates in **fish per kilometer** and **kilograms per kilometer** for each study site.

	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
YAMPA RIVER	SEVENS							
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	1147	1115	778	653	1136.7	1004.5	633.1	491.9
Flannelmouth Sucker	395	376	296	263	413.4	411.6	361.4	227.7
Bluehead Sucker	274	238	309	120	110.5	93.5	26.0	30.1
Roundtail Chub	73	41	54	29	43.8	26.6	13.6	14.9
LONG REACH	DUFFY							
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	387	403	316	430	509.6	453.8	340.5	291.9
Flannelmouth Sucker	25	15	11	5	34.2	19.3	15.6	6.1
Bluehead Sucker	24	23	16	19	14.0	9.5	10.1	12.1
Roundtail Chub	12	25	5	10	12.0	26.6	5.1	9.6
MAPPED REACH	DUFFY							
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	435	343	467	716				
Flannelmouth Sucker	13	5	9	9				
Bluehead Sucker	21	10	12	3		2.6	4.1	2.1
Roundtail Chub	16	7	7	3		3.1	1.2	0.5
YAMPA RIVER			Lily Park				Lily Park	
Species			2000	2001			2000	2001
Total Fish			6279	3168			2369	1760
Flannelmouth Sucker			2238	1667			1316	801
Bluehead Sucker			552	346			195	114
Roundtail Chub			2	2			3.0	0.1
COLORADO RIVER		CORN LAKE				CORN LAKE		
Species		1999	2000	2001		1999	2000	2001
Total Fish		3962	3417	4007		2761	2854	2605
Flannelmouth Sucker		1550	999	1662		1261	1269	1281
Bluehead Sucker		1573	1182	1272		806	504	596
Roundtail Chub		192	357	171		57	68	41
COLORADO RIVER		CLIFTON				CLIFTON		
Species			2000	2001		1999	2000	2001
Total Density estimate			3766	4547			3207	3341
Flannelmouth Sucker			1822	1563			1280	1075
Bluehead Sucker			1138	1164			452	496
Roundtail Chub			437	357			100	94
DOLORES RIVER			Big Gypsum				Big Gypsum	
Species			2000	2001			2000	2001
Total Density estimate			196.6	231.7			259.0	49
Flannelmouth Sucker			35.8	105.9			89	1.5
Bluehead Sucker			3.0	12.7			7.0	0.3
Roundtail Chub			81.0	65.1			14.9	4.5

Table 12. Density and biomass estimates in **fish per hectare** and **kilograms per hectare** for each study site.

	no./ha	no./ha	no./ha	no./ha	kg/ha	kg/ha	kg/ha	kg/ha
YAMPA RIVER	SEVENS							
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	185.2	180.0	125.6	105.4	183.5	162.1	102.2	79.4
Flannelmouth Sucker	63.8	60.7	47.8	42.5	66.7	66.4	58.3	36.7
Bluehead Sucker	44.3	38.4	49.8	19.4	17.8	15.1	4.2	4.9
Roundtail Chub	11.8	6.6	8.6	4.7	7.1	4.3	2.2	2.4
LONG REACH	DUFFY							
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	55.3	57.7	45.3	61.4	72.9	64.9	48.7	41.7
Flannelmouth Sucker	3.6	2.1	1.6	0.7	4.9	2.8	2.2	0.9
Bluehead Sucker	3.5	3.3	2.3	2.7	2.0	1.4	1.4	1.7
Roundtail Chub	1.7	3.6	0.7	1.4	1.7	3.8	0.7	1.4
MAPPED REACH	DUFFY	DUFFY	DUFFY	DUFFY				
Species	1998	1999	2000	2001				
Total Fish	85.9	67.8	92.3	141.4				
Flannelmouth Sucker	2.6	1.1	1.8	1.7				
Bluehead Sucker	4.1	1.9	2.3	0.7				
Roundtail Chub	3.1	1.3	1.4	0.7				
YAMPA RIVER			Lily Park				Lily Park	
Species			2000	2001			2000	2001
Total Fish			1047.6	528.5			395.2	293.7
Flannelmouth Sucker			373.3	278.1			219.5	133.7
Bluehead Sucker			92.1	57.7			32.5	19.0
Roundtail Chub			0.3	0.3			0.5	0.0
COLORADO RIVER		CORN LAKE				CORN LAKE		
Species		1999.0	2000.0	2001.0		1999	2000	2001
Total Fish		765.1	659.9	773.8		533.2	551.2	503.1
Flannelmouth Sucker		299.4	192.9	320.9		243.6	245.1	247.3
Bluehead Sucker		303.8	228.3	245.7		155.7	97.4	115.1
Roundtail Chub		37.0	68.9	32.9		11.1	13.1	8.0
COLORADO RIVER			Clifton				Clifton	
Species			2000	2001			2000	2001
Total Density estimate			600	724			511	532
Flannelmouth Sucker			290	249			204	171
Bluehead Sucker			181	185			72	79
Roundtail Chub			70	57			16	15
DOLORES RIVER			Big Gypsum				Big Gypsum	
Species			2000	2001			2000	2001
Total Density estimate			116.3	137.1			153.2	28.8
Flannelmouth Sucker			21.2	62.6			52.5	0.9
Bluehead Sucker			1.8	7.5			4.2	0.2
Roundtail Chub			47.9	38.5			8.8	2.6

habitat-switching pattern was also observed in 2001 when flows were dropping. Flannemouths did not occupy the eddies and pools when flow was above 120 cfs (August 22, 2001), but they were captured in these habitats as flows dropped to near 100 cfs on August 29th and September 5th, 2001.

Smallmouth bass was the only species in **Lily Park** to increase in 2001 (A-Table 1). This increase was believed to reflect a true increase in abundance, as all three Yampa sites displayed bass increases in lower-flow years. The bass density estimate at Lily Park in 2001 (501/km) was the highest of any of the sites on the Yampa River (Table 11).

The Colorado River **Clifton** site was added in 2000 because of differences in channel morphology compared with the Corn Lake site. Total density and total biomass estimates for fish/km and kg/km were similar between Corn Lake and Clifton in both years. But because Clifton was wider, the number of fish per hectare was less than Corn Lake. The total area at Clifton was 27.4 hectares compared to Corn Lake's 20.7 hectares. Both sites had a common flow of 1000 cfs. Clifton and Corn Lake were separated only by 0.2 km. So, it was possible to pool data from the sites and get larger sample sizes for testing estimates there between 2000 and 2001.

The **Clifton** site had the highest estimate of any site for total fish density per kilometer (4007/km) and biomass (3498 kg/km) (Table 11), but **Corn Lake** had the highest density 773/ha and 551 kg/ha biomass estimates by area (Table 12). The mean total fish biomass for both sites in the **15-Mile Reach** was 486 kg/ha. Biomass in the 15-Mile Reach was much higher than the Yampa River, except for the Lily Park section where it was 1.4 times higher in 2001. Biomass in the 15-Mile Reach was three to five times higher than at **Sevens** and seven to ten times higher than at **Duffy**.

The **Corn Lake** estimate in 1999 for bluehead sucker was higher than in 2000 and 2001. The density estimate for bluehead and flannemouth suckers were very similar between Corn Lake and Clifton in 2001. Bluehead sucker density was 1,272/km at **Corn Lake** and 1,206/km at **Clifton**. Flannemouth-sucker density was 1,662/km at Corn Lake and 1,619/km Clifton (Table 11).

Bluehead-sucker density and biomass estimates were higher in the 15-Mile Reach than in the Yampa and Dolores River. The bluehead sucker's mean kilogram per hectare in the **15-Mile reach** was 3.6 times higher than blueheads at **Lily Park**, 5.5 times higher than **Sevens**, and 22 times greater than **Big Gypsum** (2000 data).

Flannemouth-sucker density estimates per hectare were higher at **Lily Park** than the **15-Mile Reach**. But, because fish were smaller at **Lily Park**, **Corn Lake** had a higher biomass/ha. These data indicated that flannemouth sucker habitat at **Lily Park** was nearly as good as the 15-Mile Reach. Flannemouth sucker biomass at Lily Park was three times higher than **Sevens** and about four times higher than **Big Gypsum**.

Roundtail chub density estimates per kilometer were lower at Corn Lake (171/km), than at Clifton (370/km) (Table 11).

The largest difference between Corn Lake and Clifton in 2001 was in carp abundance (Table 11 and 12). Carp were found to be more mobile than other species between sampling trips. Near the end of sampling in 2001 when flow was lowest, habitats that formerly had a large number of carp at Corn Lake were vacant of carp and it appeared relatively more carp were found in Clifton. In spite of minor differences in density for carp, catfish and white suckers, productivity was very similar between the Corn Lake and the Clifton Stations.

Total fish density and biomass were very different between years at the **Big Gypsum Site** on the **Dolores River**. Base flows were similar between 2000 and 2001 (50 to 60 cfs), but there was a large difference in spring flows. Runoff flows were mild in 2000 with a peak flow of 1170 cfs on May 1, 2000, and peak flow was 533 cfs in 2001. The mean flow for the period April 17 through May 30 was 522 cfs in 2000, but was only 170 cfs in 2001. Reduced spring flows probably caused the lower biomass in 2001.

Dolores River density estimates for native fish >15 cm were low compared to the Colorado and Yampa (Table 11 and 12). The bluehead-sucker estimate was higher in 2001 (13 fish/km) than in 2000 (3 fish/km) due to a higher number of yearling fish in 2001. The Dolores had the lowest bluehead-sucker density estimate of all sites in 2000, but was higher than Duffy in 2001.

Flannemouth density at Big Gypsum was significantly higher in 2001 at 106/km than 2000 at 36/km (Table 11). The higher flannemouth abundance in 2001 resulted from a strong yearling group (13 - 18 cm), which was not as high the year before. The low density of adult size native fish in the Dolores River did not appear to be due to lack of recruitment, since juvenile fish were extremely abundant.

It appeared that the Dolores river was a much higher availability of YOY and yearling habitat than it had habitat for adult-sized (>28 cm) fish. Density estimates of roundtail chub were less in 2001 (65/km) than in 2000 (81/km). In 2000, there was a very high number of yearling chub (12 – 19 cm) collected, but the number of yearling fish caught in 2001 was much lower. Either there was poor survival of yearling chub or zero growth in chub since the number of larger fish did not increase.

HABITAT QUANTIFICATION

General Site Description

The Clifton reach on the Colorado River was the longest of the sampling sites followed by Corn Lake, Big Gypsum, Lily Park, Sevens and Duffy Tunnel (Table 13). The Clifton reach had a riffle run morphology with a mean slope of 0.2%. An abandoned diversion dam, in the lower part of the site, backed up sediment and created an astomosing channel morphology through much of the Clifton site. Downstream of the dam, the channel was straight and narrow where it entered the Corn Lake reach. The mean width at Clifton was 59 m at 600 cfs (Table 13).

The Corn Lake Reach was located immediately downstream of the Clifton Reach on the Colorado River. Corn Lake had the same riffle run morphology, but was narrower and more constrained than the Clifton Reach. The slope of the Corn Lake was 0.15 percent. The site had the highest mean velocity of all sites. Aerial photograph analysis of the entire 15-mile reach revealed that Clifton site was slightly wider than most of the 15-Mile Reach while the Corn Lake site was slightly narrower. Mean width of Corn Lake was 48 meters at 600 cfs (Table 13)

The Duffy Tunnel on the Yampa River was the widest station with a mean width of 68 m at 600 cfs. Duffy had a low gradient riffle run / pool riffle (slope 0.06%) (Table 13). A significant feature of the Duffy Tunnel Reach was the “Duffy Tunnel” itself, a water diversion in the middle of the sampling reach. Large boulders were located in the channel just downstream of the diversion. In this area the channel widened considerably into an island complex. The Duffy Tunnel Reach was comprised of four runs and three riffles, each riffle being associated with an island complex.

The Sevens site had a mean width of 60 m at 600 cfs, with a slope of 0.05 percent (Table 13). Sevens mirrored the same low gradient riffle run / pool riffle morphology as Duffy Tunnel. The Sevens Reach had a single-thread channel with the upper portion of the channel consisting of tightly spaced pools and riffles (~7.5 channel widths between riffles). The lower 900 meters was one large run.

Lilly Park was steeper, faster, and narrower (Table 13) than the other Yampa River sites and had a characteristic change in morphology between the upper and lower sub-reaches. The upper portion of the reach was shallow with riffle-run morphology. Half way through the reach was a large bend. Below that point the river had tightly spaced pool-riffle sequences (~5 channel widths between riffles).

Mean bed slope was determined from the longitudinal profiles for each site. Negative slopes on the profile occurred in riffles and runs. Positive or up-slopes occurred in glides or in the tail out of pools. The Corn Lake and Clifton longitudinal profile see Appendix-Figures 1 and 2. Lilly Park has the highest bed slope and the highest standard deviation suggesting higher variability at this station (A-Figure 3). Longitudinal profiles for Sevens, Duffy and Big Gypsum are presented in (A-Figure 4, 5 and 6 respectively).

Habitat Composition and Habitat Diversity

The surface area of the 16 meso-habitats types was used to determine habitat composition at each site for each simulated flow. The 16 meso-habitat types were composed of five pools, five runs, four riffles and two rapids (Table 4). The flow at the time of fish sampling was used to compare habitat composition and diversity between rivers. For the Colorado River this flow was 1000 cfs. Only about 7% of the habitat was in the pool category (Table 14). Clifton had about 17% pool and backwater at 1000 cfs. Lilly Park was 19% pool habitat at 250 cfs (Table 14). At 250 cfs Lilly Park, Sevens and Duffy were dominated by run habitats. Pools were common in the main channel (Table 14).

Table 13. Physical attributes of each study site (mean velocity, length, mean width, surface area at modeled flows).

	Big Gyp	Clifton	Corn Lake	Duffy	Lilly	Sevens
*Mean Velocity (m/s)	0.28	0.44	0.54	0.39	0.51	0.38
Length (km)	3.3	4.2	3.9	2.1	3.1	2.9
*Width (m)	22	59	50	68	57	60
Percent Slope	0.15%	0.20%	0.16%	0.06%	0.20%	0.05%
Flow (cfs)	Area (ha)					
10	6.0					
20	6.3					
30	6.5					
40	6.7				12.9	11.8
50	6.8					
60	6.9			10.8	12.9	13.1
80	7.0			11.2	12.9	13.7
100	7.1	16.4	11.2	11.6	13.1	14.3
125				11.9		
150		18.5	15.5	12.2	14.4	15.1
200	7.6	19.6	16.3	12.6	14.9	15.6
250		20.6	17.0	12.9	15.1	15.9
300	7.8	21.3	17.7	13.2	15.1	16.2
350		21.9	18.1			
400	8.0	22.4	18.5	13.6	16.7	16.7
450		22.9	18.8			
500	8.2	23.3	19.2	13.9	17.0	17.1
600		24.2	19.8	14.2	17.6	17.4
700		25.3	20.2			
800		26.0	20.7			
880						18.1
900		26.8	20.4			
1000		27.4	20.7			
1200		28.5	22.1			
1400		29.3	22.7			
1600		30.2	23.3			
1800		31.0	23.8			
2000		31.8				

Velocities and mean width calculated at 600cfs, except for Big Gypsum which were calculated at 100cfs

Meso-habitat composition varied with discharge, since meso-habitats were defined by depth and velocity criteria. At Corn Lake and Clifton, pool composition was highest (40% and 60%) at the lowest modeled flow of 100 cfs and quickly decreased as flows increased to 800 cfs (A-Figures 11a and 11c). At 1000 cfs, Corn Lake had the highest composition of riffle habitat at 53% while Clifton had 39% (Table 14, and A-Figures 11a and 11c). At 250 cfs, the Yampa River had a low amount of riffle habitat compared to the Colorado River. Lily Park had more riffle habitat at 250 cfs (10%) than Sevens (2%) and Duffy (6%) (Table 14, A-Figures 12a, 12c, 13a).

Base flows on the Dolores River at the time of electro-fishing were about 50 to 60 cfs. Habitat composition at this flow was 51% pools and only 5% riffle (Table 14, A-Figure 13c).

The lowest of amount of riffle habitat per kilometer was at the Big Gypsum Site. The highest amount of riffle habitat was at Clifton (2.58 ha) (Table 14). These two sites also had the lowest (Big Gypsum, 259) and the highest (Clifton, 3,440) total fish biomass (kg/km). The R-square value for a simple linear regression between riffle area and total fish biomass was 0.85 (Table 15). Riffle habitat at the Duffy site was intermediate to Sevens and Lily Park. Yet, total fish biomass was much less at Duffy. Fish biomass at Duffy was likely reduced by higher predation rates. Habitat data there suggested a higher total fish biomass potential than was observed.

Table 15. Correlation between riffle meso habitat and total fish biomass

		Clifton	Corn	Lily Park	Sevens	Duffy	Big Gypsum
Riffle		2.58	2.08	0.55	0.12	0.30	0.09
Total biomass		3440	2740	2064	1071	482	259
R Square	0.847535						

Deep pools were found to be uncommon habitats in all sites. At low flows velocities are low. At high flow when depths are higher, low velocity areas are confined to backwaters. Deep pools seemed to be used primarily by larger fish including larger predators. Small fish tended to occupy shallow pools or shorelines. Species that appeared to require deep pools and runs (over 1-meter depth) included mostly channel catfish, carp and white suckers. The Clifton station, with the most deep-pool and deep-run habitat, also had the greatest combined biomass of catfish, carp and white suckers (Table 16). The R-square value for this regression was 0.89.

Table 16. Correlations between pool habitat and biomass for carp, white sucker and catfish.

		Clifton	Corn	Lily Park	Sevens	Duffy	Big Gypsum
Deep pool & deep run		1.53	1.07	0.76	0.88	0.46	0.17
tot biomass		1581	767	740	492	373	95
R Square 0.8854							

The bluehead sucker is a native fish and one of the primary species of interest for this study. Habitat requirements of this fish indicate a relationship between bluehead sucker biomass and deep-riffle meso-habitat availability. The Colorado River sites had much greater deep-riffle meso-habitat than either the Yampa and Dolores Rivers. The R-square value for deep-riffle habitat and total bluehead biomass was 0.92 (Table 17). It appeared that a lack of deep and swift habitat (deep-riffle) in the Yampa River explained why blueheads tended to be smaller at Lily Park. The Duffy site had lower bluehead sucker biomass relative to the other Yampa River sites and relative to riffle habitat availability. This was explained by hybridization with the white sucker.

Table 17 Correlation between deep riffle habitat and bluehead sucker biomass

		Clifton	Corn	Lily Park	Sevens	Duffy	Big Gypsum
Deep riffle		1.53	1.41	0.05	0.02	0.01	0.00
Bluehead biomass		497	550	195	102	12	7
Bluehead R Square		0.9158					

Habitat diversity based on the 16 meso-habitat compositions varied greatly among sites. The Shannon Weaver diversity at the base flow representative of the fish surveys was highest at Clifton followed by Corn Lake, Big Gypsum, Lily Park, Sevens and Duffy (Table 14). A visual display of habitat diversity for each simulated flow is given in Appendix Figures 11, 12 and 13.

The maximum Shannon-Weaver value for 16 meso-habitats was 2.776. Habitat diversity (Shannon-Weaver) peaked at 1000 cfs at Clifton (2.47) and at 1200 cfs at Corn Lake (2.23), which were typical of flow conditions during the fish-sampling period. Since flows were not modeled above 600 cfs for the Yampa River, the flow that habitat diversity peaked was not identifiable. However, at 600 cfs Lily Park had the greatest habitat complexity according to Shannon-Weaver diversity (2.22) followed by Sevens (1.92). Duffy was the least complex (1.73). This order of habitat complexity matches the order of fishery diversity found on the Yampa River.

Habitat Suitability

We used the finer scale (Polygon) method to determine fish habitat suitability criteria based on how fish distributed themselves within the study site. Polygons were sub units of a study site and possessed both electro-fishing and habitat data. The polygon analysis referred to the process where biomass was used to identify suitable and non-suitable habitats. Habitat suitability for bluehead and flannemouth suckers was calculated at Corn Lake, Clifton, Lily Park and Sevens (A-Table 3, 4, 5, and 6 respectively). Polygon data from Duffy was not included due to the very low occurrence of native suckers there (A-Table 7). Polygon data from the Big Gypsum site was not included because the 2-D model simulations were not available when this analysis was performed. Inclusion of the Big Gypsum data would likely not alter results because at 50 to 60 cfs the Big Gypsum site lacked both habitat and biomass diversity.

In 2000 and 2001, shoreline electro-fishing was done at Corn Lake and Clifton to sort out bank habitat from mid-channel habitat. Very few adult bluehead and flannemouth suckers were collected along from the shoreline making it unnecessary to keep shoreline polygons for these fish. The adult bluehead and flannemouth sucker did not occupy bank habitat. This was another indication that these fish avoid areas with depths less than 0.3 m and velocities less than 0.35 m/s.

The polygon analysis found that bluehead sucker biomass increased in polygons with higher velocities (A-Tables 3, 4, 5, 6 and 7; A-Figure 14a). Polygons that had velocities over 0.6 m/s had much higher biomass than polygons with velocities less than 0.5 m/s. There were no polygons with a mean velocity over 0.6 m/s on the Yampa River.

All polygons with higher velocity criteria were on the Colorado River data. The bluehead sucker Sigma plot (A-Figure 14a) also showed mean depths of 0.5 to 1.0 m having higher biomass than shallower depths.

The sigma plot for flannemouths showed these fish were more abundant in polygons with mean velocities over 0.5 m/s and depths over 0.6 m (A-Figure 14b).

The sigma plot representation was simplified into four functional meso-habitat types based on depth and velocity characteristics. The poorest habitat for blueheads was classified as **Unusable** (Figure 7) and represented the river areas that blueheads did not occupy. Polygons with the highest biomass were used to indicate **Optimal** habitat conditions (depths and velocities). Optimal polygons accounted for about 60% of the total bluehead biomass. The mean biomass for all optimal biomass polygons was found to be about 243 kg/ha (Figure 7). **Marginal** habitat represented about 25% of the total biomass. The mean biomass for polygons in the marginal category was 116 kg/ha. The remaining 15% of the total biomass represented the **Unsuitable** category (Figure 7). Unsuitable habitat had a biomass value of 31 kg/ha.

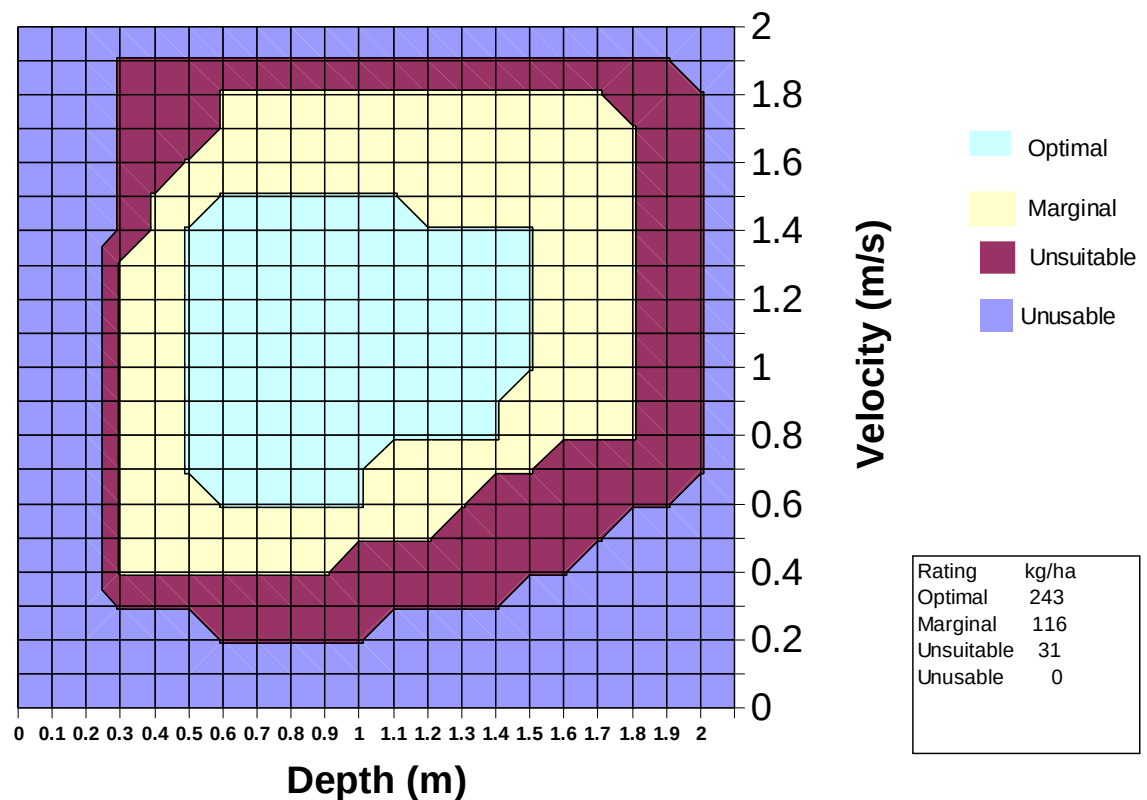


Figure 7. Depth and velocity criteria used to model bluehead habitat availability.

Habitat suitability criteria for flannelmouths were also developed using the above-described polygon analysis approach. The sigma plot for flannelmouths showed biomass associated with mean depths and velocities for that polygon (A-Tables 3, 4, 5, 6, and 7). Very few flannelmouth were observed from habitats with velocities less than (0.3 m/s) (A-Figure 14b). **Unusable** habitat for flannelmouths represented the river areas where they were not found. **Optimal** polygons accounted for about 60% of total biomass. The mean biomass for all optimal biomass was found to be about 496 kg/ha (Figure 8). **Marginal** habitat represented about 25% of the total biomass and was 253 kg/ha. **Unsuitable** was about 15% of the total biomass and was a value of 123 kg/ha.

The higher biomass for flannelmouths resulted primarily from their larger body size. Larger flannelmouths were more frequent in the Colorado River than in the Yampa. Also flannelmouth and bluehead densities were fairly similar in the Colorado River. But, in the Yampa River flannelmouths had much greater density than the bluehead.

Development of biologically based habitat suitability criteria made it possible to determine the relationship between flow and habitat availability. The suitability criteria were validated by the high R-square value for the regression between observed and predicted biomass values for the bluehead (0.91) and flannelmouth (0.93).

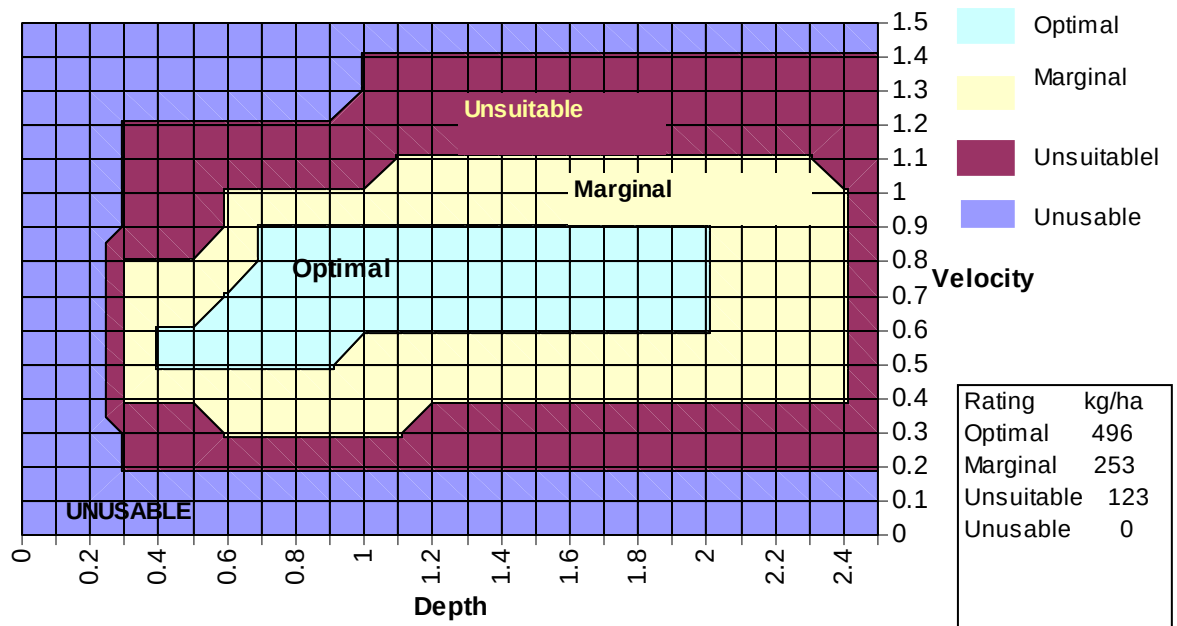


Figure 8. Flannelmouth sucker depth and velocity criteria used to model bluehead habitat availability.

HABITAT AVAILABILITY VERSUS FLOWS

Habitat availability for each of the four functional meso-habitat types (Optimal, Marginal, Unsuitable and Unusable) was calculated using the 2-D flow model data for simulated flows at each site. The habitat suitability graphs were the final product in the Meso-Habitat methodology and showed how total habitat was related to flow. The functional meso-habitat graphs were for adult (>20 cm) bluehead and flannelmouth suckers. Optimal habitat represented about 60% and Marginal habitat represents about 25% of the total biomass. The Unsuitable habitat represented about 15% of the biomass and Unusable supported zero biomass. At low flows, Unusable habitat always increased the area and percentage of blueheads and flannelmouths since both depths and velocities decreased.

– Bluehead sucker

Flows modeled at **Corn Lake** ranged from 100 to 1800 cfs. Unusable habitat decreased rapidly from 150 to 800 cfs and was fairly constant from 1000 to 1800 cfs. Optimal habitat increased with increasing flow up to 1200 cfs. Above 1200 cfs optimal habitat increased at a slower rate. Both marginal and unsuitable peaked at near 500 cfs (Figure 9).

The range of flows modeled at **Clifton** ranged from 100 to 2000 cfs. Clifton had more total surface area than Corn Lake. There was about four ha more of the Unusable habitat at Clifton than at Corn Lake. The wider channel and higher amount of pool habitat at Clifton did not translate to increased habitat or abundance of blueheads. The Unusable area peaked at 16 ha, remaining high at 10 ha at 1500 cfs (Figure 10). Optimal habitat increased linearly from 300 to 1800 cfs. At 1000 cfs, Optimal habitat was near six ha while Marginal habitat was also near six ha, similar to Corn Lake. Marginal habitat had an inflection point at 700 cfs. Unsuitable habitat had an inflection point at 300 cfs (Figure 10).

Flows modeled at **Lily Park** ranged from 40 to 600 cfs. At the start of the project we believed that 600 cfs would be high enough to be inclusive for making instream flow recommendations. Nonetheless, relationships between flow and the functional meso-habitat types would have been clearer if flows had been modeled up to at least 1000 cfs. Unusable habitat decreased fairly linearly from 40 (12.5 ha) to 600 cfs (six ha). Unsuitable habitat peaked at about 250 cfs and was fairly constant above this flow. Below 250 cfs, Optimal habitat availability was very low. At 600 cfs, Optimal habitat increased to two ha, which was very similar to availability on the Colorado River (three ha at Corn Lake and two ha at Clifton). Marginal habitat was near zero at 100 cfs and increased to five ha at about 500 cfs (Figure 11), which was also similar to the two Colorado River sites.

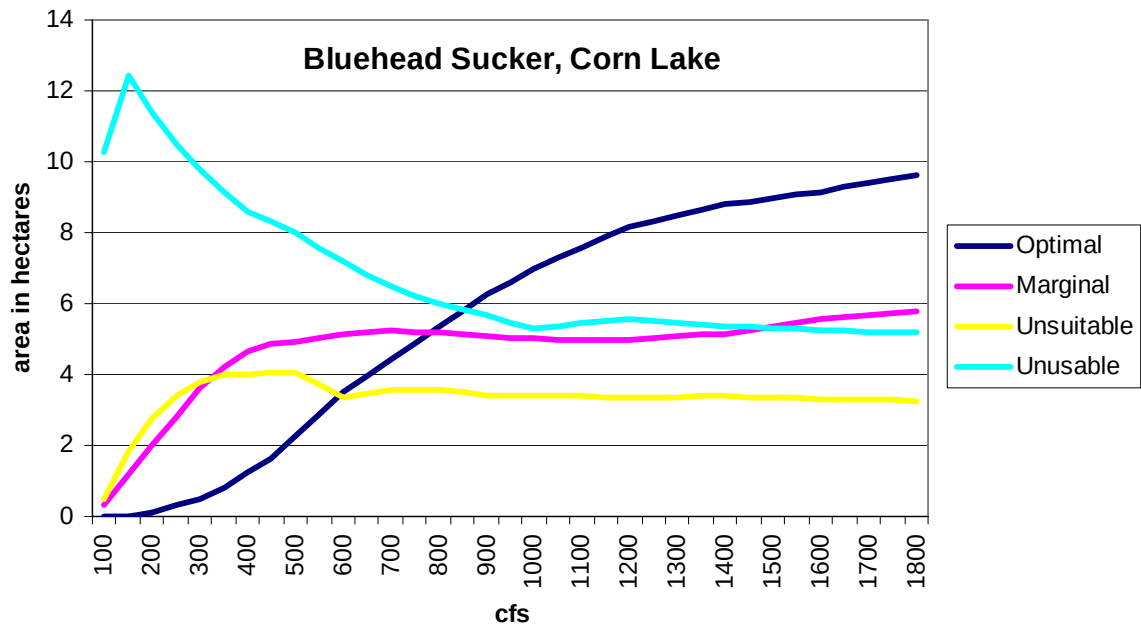


Figure 9. Bluehead sucker habitat availability at Corn Lake, Colorado River.

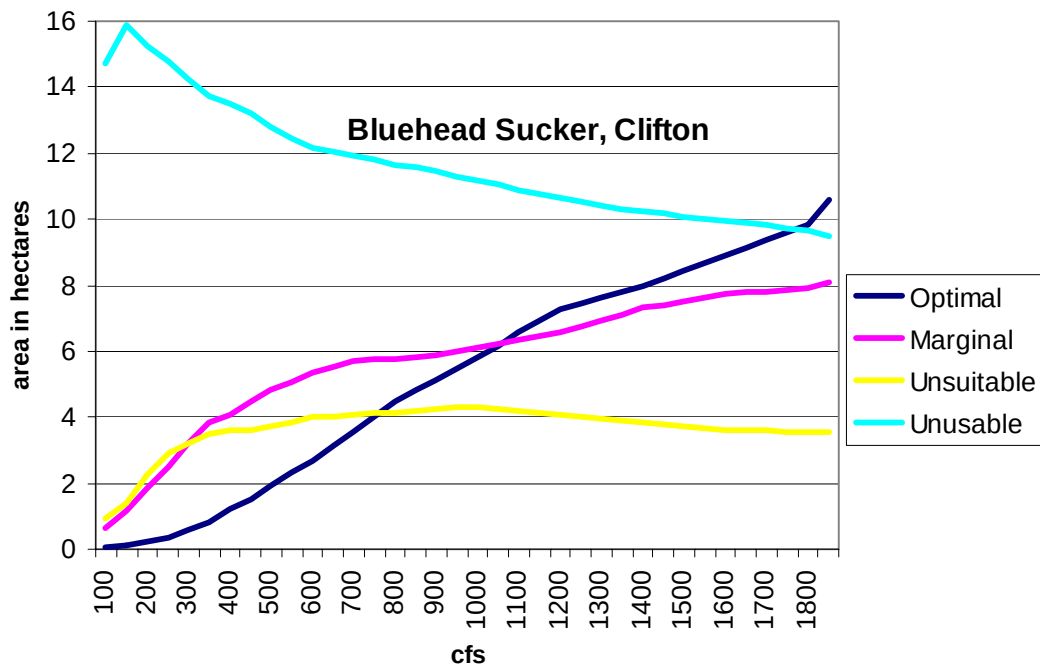


Figure 10. Bluehead sucker habitat availability at Clifton, Colorado River.

Flows modeled at **Sevens** ranged from 40 to 880 cfs. At flows less than 100 cfs nearly 100% of the river was in the Unusable habitat category. Unusable habitat was about six ha at 550 cfs. Marginal habitat peaked near 5.5 ha at 550 cfs (Figure 12). Optimal was only one ha at 600 cfs, about half that found at Lily Park and the Colorado River sites. Optimal habitat availability increased to over four ha at the highest modeled flow of 880 cfs and the rate of increase was faster above 600 cfs. The rapid increase in Optimal habitat indicated that depths and velocity increased more quickly above 600 cfs than below 600 cfs. Flows less than 250 cfs produced a very low amount of adult bluehead sucker habitat in the Marginal and the Optimal categories (Figure 12)

Flows modeled at **Duffy** ranged from 40 to 600 cfs. At 600 cfs, marginal habitat was at 3.9 ha and Optimal was less than 1 ha. Like Sevens, Duffy has a flat slope and did not appear to have high potential for a large bluehead-sucker population at flows less than 250 cfs. Unusable habitat at Duffy peaked at 125 cfs and was the most common habitat type until flows reached 500 cfs (Figure 13).

Flows modeled at **Big Gypsum** ranged from 10 to 500 cfs. These ranges appeared adequate to bracket curve breaks for both higher and lower base flows. Curve breaks for Unusable, Unsuitable and Marginal were all near 200 cfs (Figure 14). Flows less than 80 cfs provided less than 0.6 ha Optimal habitat. Wetted width at Big Gypsum was less than half that of the Yampa and Colorado rivers, so hectare per unit discharge was less.

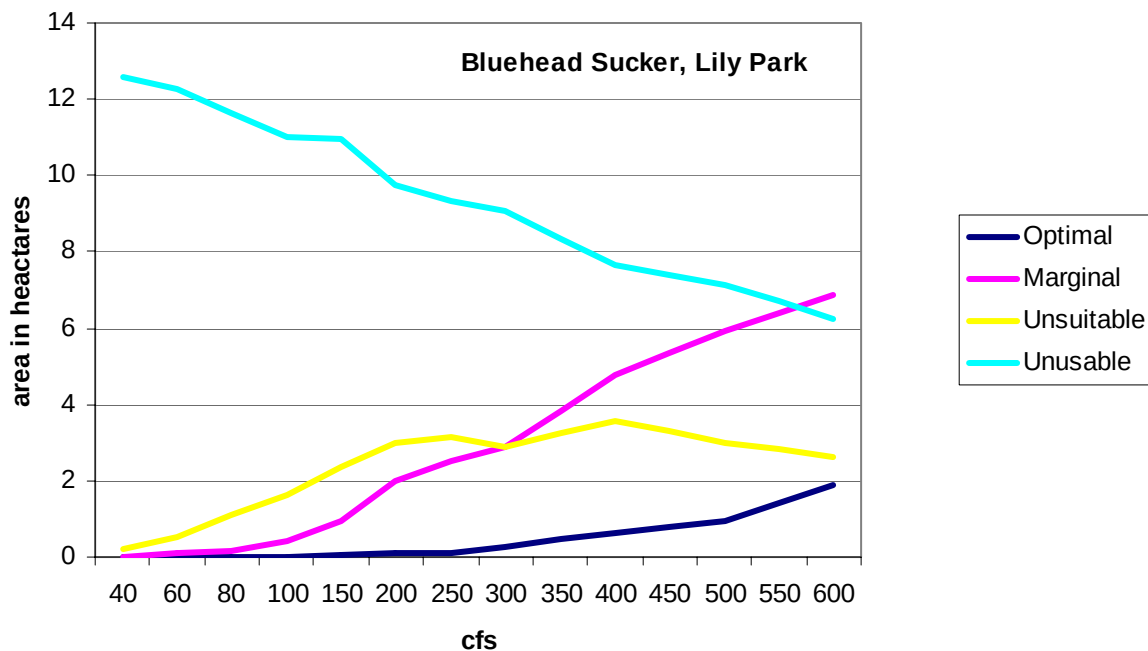


Figure 11. Bluehead sucker habitat availability at Lily Park, Yampa River.

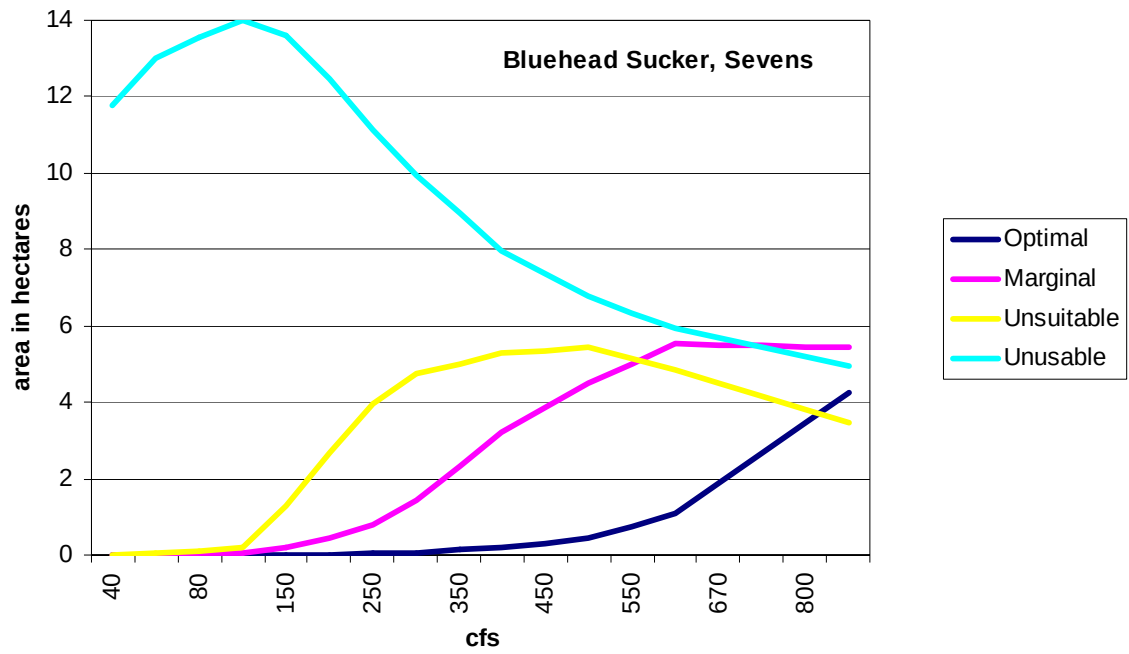


Figure 12. Bluehead sucker habitat availability at Sevens, Yampa River.

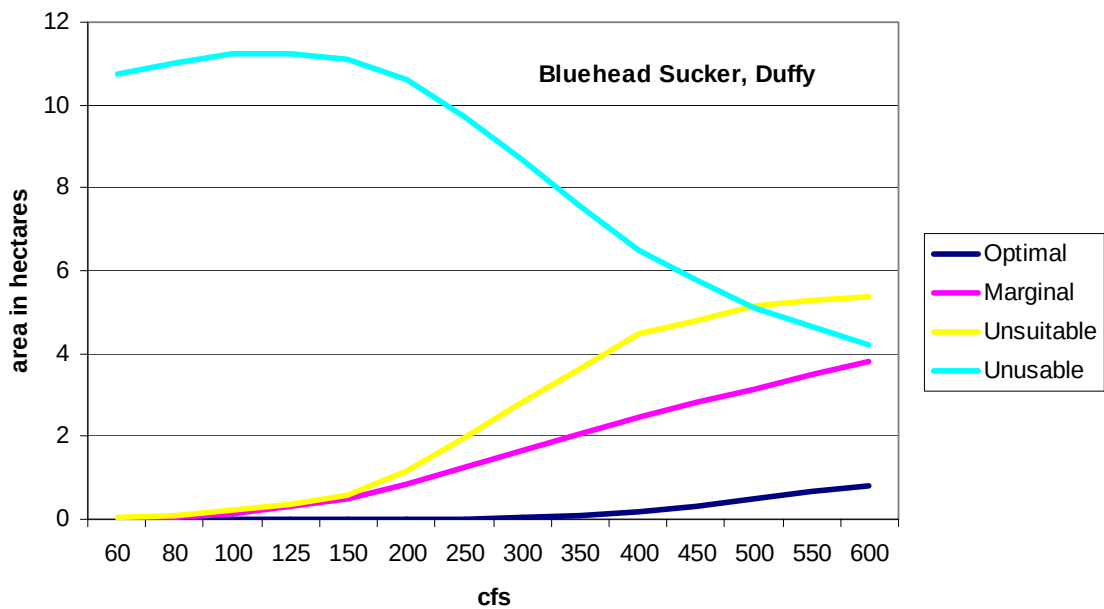


Figure 13. Bluehead sucker habitat availability at Duffy, Yampa River.

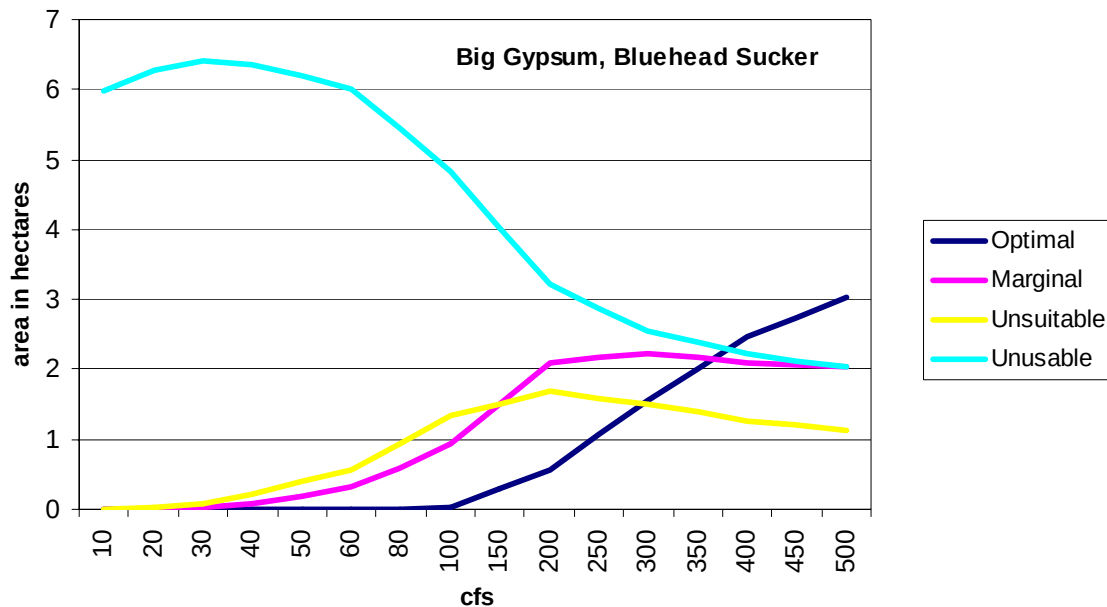


Figure 14. Bluehead sucker habitat availability at Big Gypsum, Dolores River

When habitat availability (Figures 9 to 13) in hectares is multiplied by the mean biomass associated with each habitat type (Optimal, Marginal and Unsuitable) the product represents a biomass projection for each simulated flow. The mean biomass for blueheads was zero in Unusable habitat (polygons), 31 kg/ha for Unsuitable polygons, 116 kg/ha in Marginal and 243 kg/ha in Optimal polygons (Figure 7). The biomass projection curve was therefore a composite of the four functional meso-habitat types, which simplified comparisons of habitat availability between sites.

The Big Gypsum site had higher projected biomass at lower flows than the other sites (Figure 15). Big Gypsum had a much narrower wetted width (18.5 m) and a fairly high bed slope of 0.15%. The smaller channel meant suitable depths and velocities were achieved at lower flows. Big Gypsum also had the highest projected bluehead biomass of 121 kg/ha at 500 cfs (Figure 15). There was a curve inflection in the Big Gypsum projection curve at 80 cfs and another at 200 cfs. Below 80 cfs, bluehead biomass was computed to be less than 5 kg/ha, which was near the flow and biomass observed during data collection.

The Corn Lake site had the highest projected biomass for flows over 250 cfs for the large rivers (Figure 15). Corn Lake has a narrowest stream width (48 m) of the Colorado and Yampa River sites and a higher bed slope of 0.15%. Since discharge equalled width x depth x velocity, the narrower width at Corn Lake produced higher mean depth and/or velocity values for the higher range of flows. The Corn Lake

bluehead biomass curve had its steepest slope below 600 cfs. At base flows of near 1000 cfs, biomass at Corn Lake was projected to be near 115 kg/ha. Corn Lake was sampled during three years and bluehead biomass was observed to be near 110 kg/ha at base flows of near 900 to 1000 cfs.

Lily Park had the highest projected biomass of blueheads at flows less than 250 cfs (Figure 15). The higher mean bed slope (0.2%) accounted for more biomass potential at lower flows than at Corn Lake. The projected biomass curves at Lily Park and Corn Lake were very similar, which meant physical habitat was very similar for these two sites. The most obvious physical difference between these two sites was the level of their base flows. Given similar base-flow scenarios, the two sites were expected to have similar bluehead population characteristics. The deeper and faster habitats and larger-sized bluehead suckers, common at Corn Lake, were lacking at Lily Park. In 2001 the bluehead biomass estimate was about 32 kg/ha at Lily Park.

The Clifton site had the third highest predicted bluehead biomass for flows from 100 cfs to 600 cfs among the large rivers studied. Wetted width (60 m) and mean bed slope (0.2%) were also high at Clifton. Even though bluehead population characteristics were nearly identical between Clifton and Corn Lake, biomass projections were less at Clifton because of higher total surface area there. The greater amount of off-channel or backwater habitat at Clifton was found to be unusable habitat for adult blueheads. Figure 15 indicates that at a flow of 600 cfs, bluehead biomass was expected to be very similar for Clifton, Sevens and Duffy.

Sevens and Duffy had similar wetted widths of 60 m and 68 m respectively and the lowest mean bed slopes (0.05% and 0.06% respectively) of the six study sites. The flatter nature of the two sites was reflected in a reduced amount of bluehead potential. At 400 cfs, the bluehead biomass was projected to near 35 kg/ha. It quickly dropped to six kg/ha at a flow of 150 cfs for both sites (Figure 15).

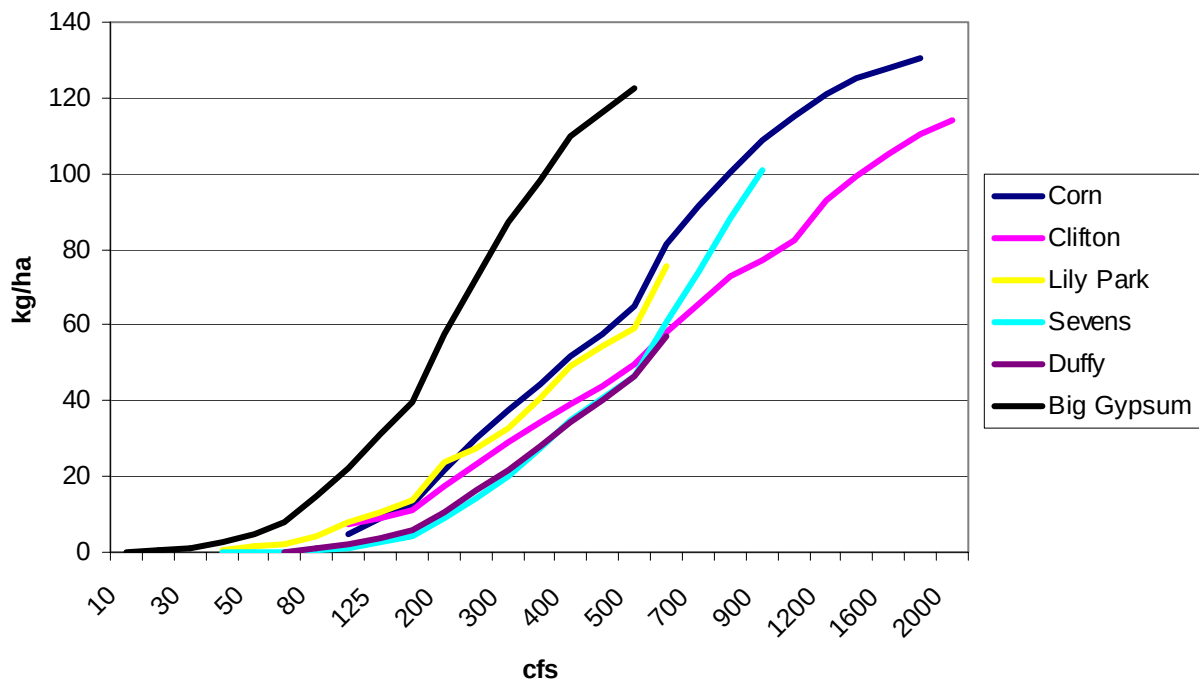


Figure 15. Projected biomass (kg/ha) of blueheads based on habitat availability over a range of simulated flows.

The projected adult bluehead biomass was regressed against the measured biomass for all stations with data except for Duffy. Duffy was excluded because non-hybridized blueheads were very rare at that site, a condition amplified by predation and not due strictly to habitat availability. Measured biomass was the kg/ha of blueheads determined by fall electro-fishing. To make the comparison between measured and predicted biomass, it was necessary to select a flow that represented the base flow for that year's sample. Some years have higher base flows than others, but the minimum flow likely does not set carrying capacity for the entire year since it only occurs for a single day (Table 19). The median flow (177) had an even number of days above and below this level (Table 19). The 60-day low-flow was selected as the flow to use for the comparison between measured and projected biomass. The 60-day low-flow day meant there were 59 days in the water year with less flow and 305 days with higher.

Table 18. The 1, 10, 20, 40, 60, 100 and 177 low-flow days for the Maybell, Lily Park, Palisade and Bed Rock gages for years with fishery biomass data.

1998	1	10	20	40	60	100	177
Maybell	115	170	194	280	350	500	808
Lily Park	157	210	241	340	433	540	802
1999	1	10	20	40	60	100	177
Maybell	110	176	212	247	290	362	469
Lily Park	110	210	226	274	327	400	490
Palisade	435	710	1190	1380	1510	1720	1970
2000	1	10	20	40	60	100	177
Maybell	30	50	67	113	199	275	352
Lily Park	30	70	99	125	196	303	364
Palisade	581	694	749	901	1090	1620	1880
Bed Rock	25	33	37	48	52	54	59
2001	1	10	20	40	60	100	177
Maybell	50	70	94	123	160	210	255
Lily Park	67	95	126	160	201	240	280
Palisade	477	580	690	828	927	1080	1340
Bed Rock	26	32	36	38	42	45	52

The R square value for the project versus measured biomass of 0.91 indicated that this analysis gave a good reflection of the measured data (Figure 15). The highly significant relationship was due to the wide range of flow conditions used in development of the Meso-habitat model. Flows less than 800 cfs during the base flow period were not common on the Colorado River and base flows were generally less than 300 cfs on the Yampa River. Additional data for this validation approach will become available when fish sampling is conducted at the Colorado and Yampa River sites in 2003 and when a site on the Gunnison River is added in 2005.

– *Flannemouth sucker*

Flannemouth habitat data was analyzed in the same manner described for bluehead sucker. In general, flannemouths were found to prefer habitats with somewhat less velocity and greater depths than blueheads. Flannemouth and bluehead density estimates were similar for the Colorado River, but biomass estimates for flannemouths were higher because these fish achieve a larger body mass. On the Yampa River, flannemouths had higher density and biomass estimates than bluehead sucker at all three sampling sites.

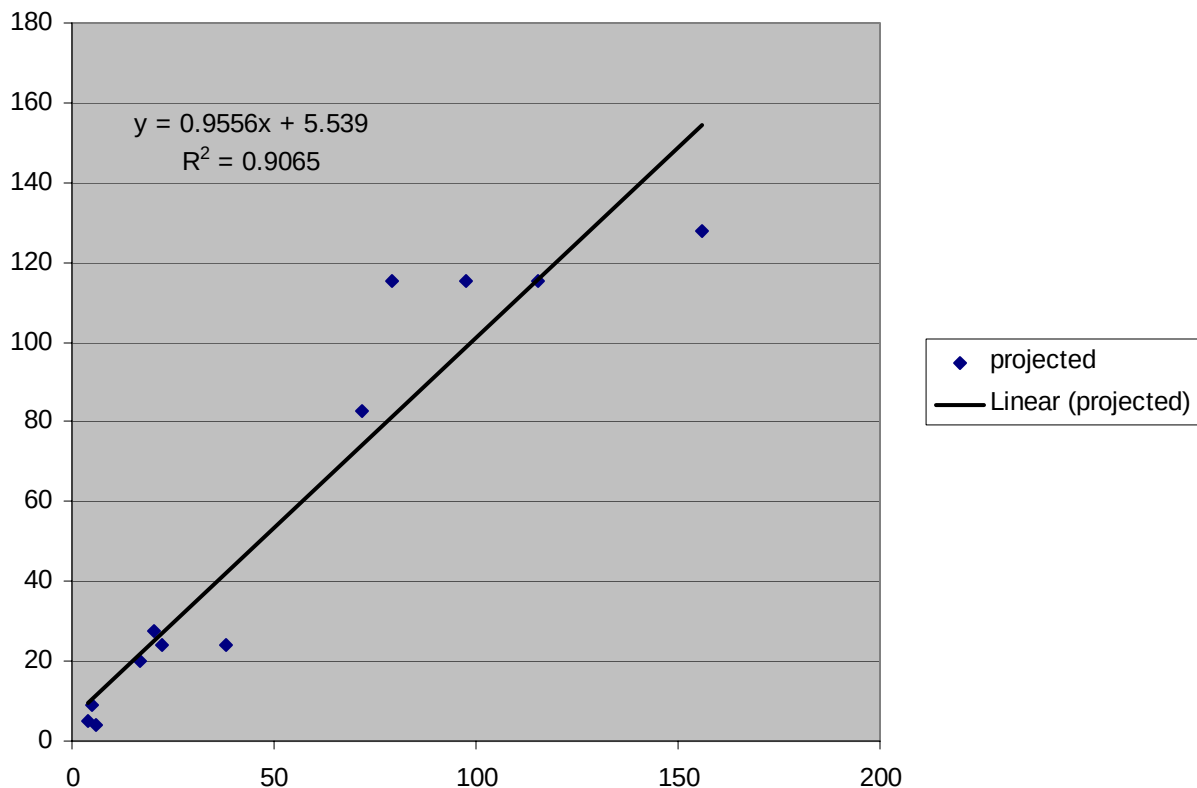


Figure 16. Projected versus observed bluehead biomass for five study sites.

The flows modeled at **Corn Lake** ranged from 100 to 1800 cfs. **Unusable flannemouth habitat was minimized near 5 ha in the flow range of 800 to 1000 cfs.** Sampling on the Colorado River in 2000 and 2001 was performed at flows in the 900 to 1000 cfs ranges. These flows appeared to provide near maximum habitat for flannemouths. Flows over 1200 cfs do not improve habitat availability for flannemouths. Optimal habitat was highest at about 5.5 ha (1000 cfs), while Marginal habitat peaked at 7 ha at 1200 cfs. There was an inflection of the Marginal habitat curve at 500 cfs indicating a rapid decline in flannemouth habitat when flows drop below 500 cfs (Figure 17).

The flows modeled at **Clifton** ranged from 100 to 2000 cfs. Clifton had about 4 to 5 ha more of the Unusable category than Corn Lake at similar flows. Unusable area peaked at 15 ha at 100 cfs and was at its minimum, 10 ha, at a flow of 800 cfs (Figure 22). Optimal habitat increased linearly from 10 to 1100 cfs. At flows of 1200 to 1500 cfs, flannemouth habitat was maximized at the Clifton station. At 1500 cfs, both Marginal and Optimal habitats were near 7 ha. Marginal habitat had an inflection point at 700 cfs and Unsuitable habitat had an inflection point at 300 cfs (Figure 18).

Flows modeled at **Lily Park** ranged from 40 to 600 cfs. Unusable habitat decreased fairly linearly from 40 (12 ha) 600 cfs (5 ha). Unsuitable habitat peaked from

250 cfs to 400 cfs. The maximum optimal habitat likely occurred at a flow higher than 600 cfs. At 600 cfs, Optimal was four ha and Marginal was five ha. At 600 cfs Lily Park was very similar in habitat availability to both Colorado River sites. Below 200 cfs, Marginal habitat decreased and Optimal habitat became rare. Below 100 cfs Marginal habitat was very poor and Optimal was near zero (Figure 19).

Flows modeled at **Sevens** ranged from 40 to 880 cfs. At flows less than 100 cfs, nearly all habitat was in the Unusable category at 12 to 14 ha. Unusable habitat was below four ha at flows over 600 cfs. Marginal habitat peaked near 6 ha at 600 cfs (Figure 20). Only one ha of Optimal habitat occurred at 450 cfs. There were less than 3 ha at 600 cfs. At flows over 600 cfs, Optimal habitat increased at a faster rate and was about 6 ha at the highest modeled flow of 880 cfs. At flows less than 200 cfs, very little river area was in either the Marginal or Optimal categories for flannelmouths.

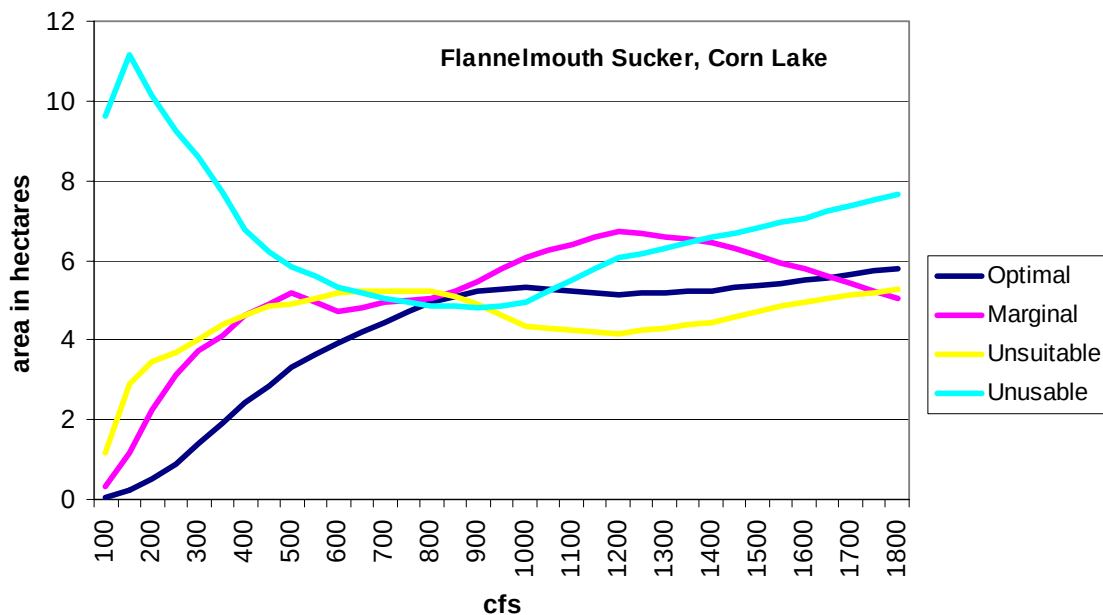


Figure 17. Flannelmouth sucker habitat availability at Corn Lake, Colorado River.

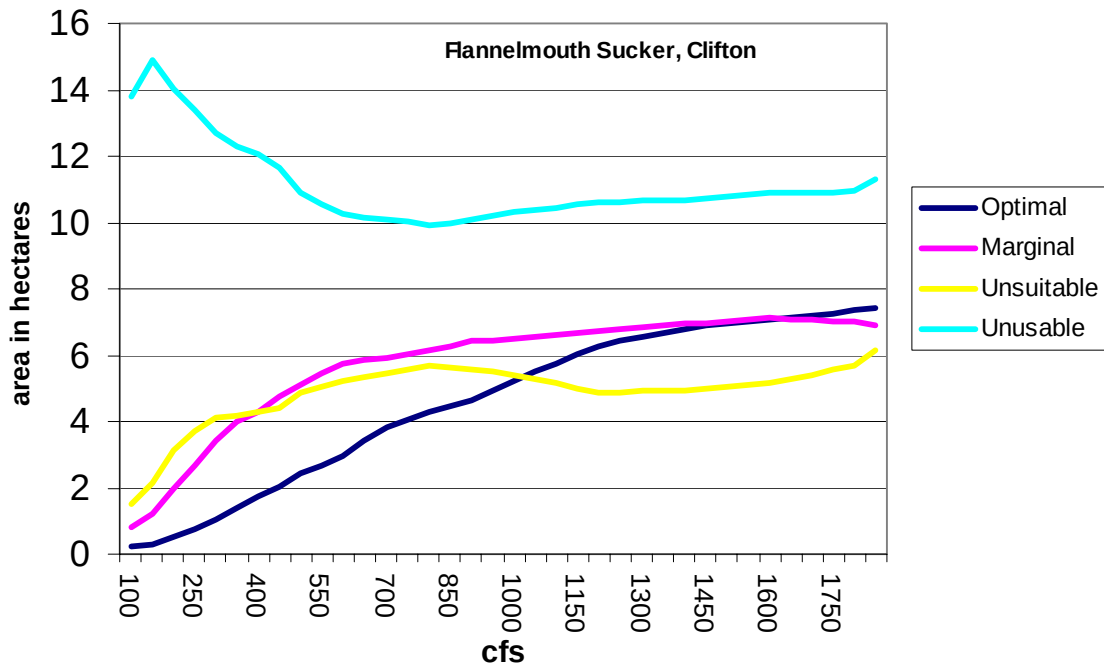


Figure 18. Flannemouth sucker habitat availability at Clifton, Colorado River.

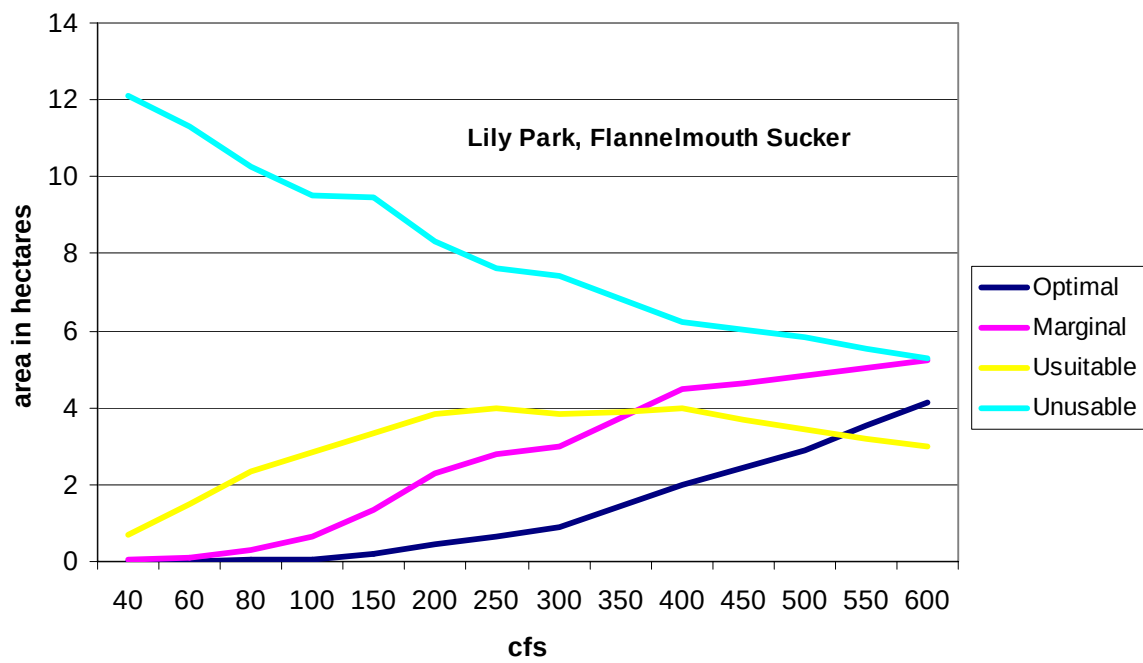


Figure 19. Flannemouth sucker habitat availability in ha at Lily Park, Yampa River.

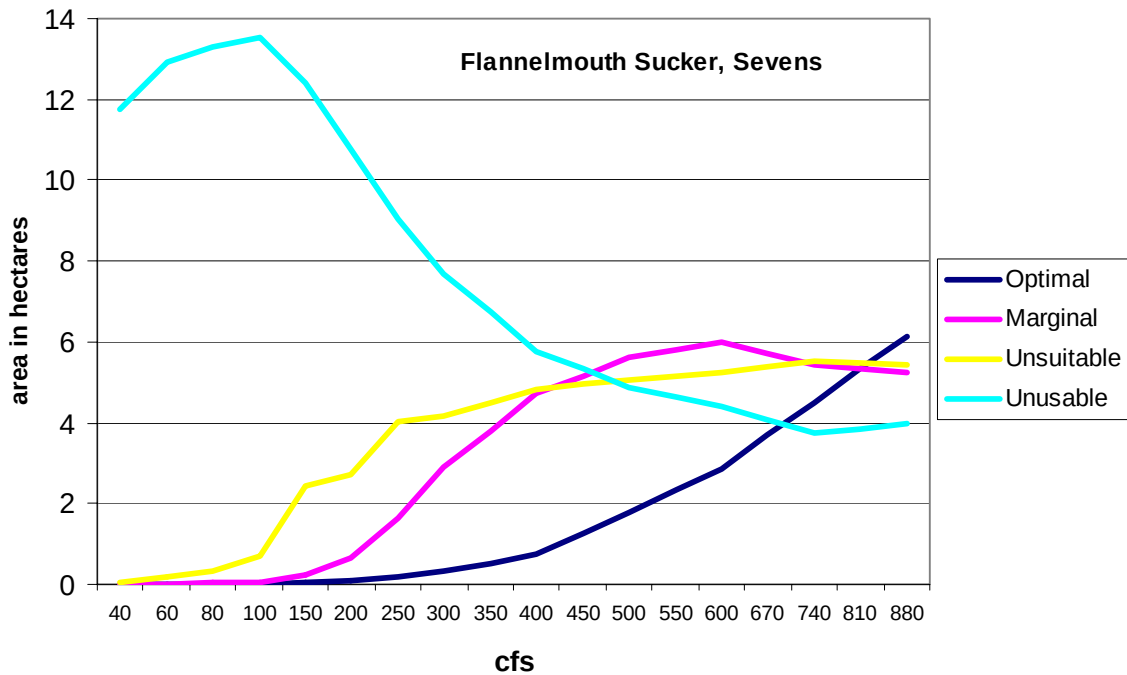


Figure 20. Flannemouth sucker habitat availability in ha at Sevens, Yampa River

Flows modeled at **Duffy** ranged from 40 to 600 cfs. Unusable habitat at Duffy peaked at about 11 ha at 100 cfs and was the most common habitat type until flows reached 400 cfs (Figure 21). At 600 cfs unusable habitat was less than 3 ha. Unsuitable habitat was highest at 400 cfs. Marginal habitat increased slowly from 60 to 300 cfs. Optimal habitat was about 1.5 ha at 600 cfs. Duffy appeared to have the least amount of flannemouth sucker habitat of the study sites in the lower ranges of flows

Flows modeled at **Big Gypsum** ranged from 10 to 500 cfs. Unusable habitat dropped from a high of 6 ha to about 1.7 at 150 cfs. Optimal habitat increased steadily from 100 to 550 cfs (Figure 22). Flows over 150 cfs did not improve marginal habitat. Flows less than 80 cfs did not provide optimal flannemouth habitat. Flows less than 40 did not provide marginal habitat. The Big Gypsum station was sampled at a flow near 60 cfs, but flows can get well below 60 cfs in some years.

Adult flannemouth (>20 cm) biomass was projected for each simulated flow by multiplying habitat availability (ha) times the mean biomass for each type. Unusable habitat had a zero biomass value. Unsuitable had a mean biomass of 123 kg/ha. Marginal had a mean biomass of 253 kg/ha Optimal was 496 kg/ha. The projected biomass curve was a composite of these four functional meso-habitat types.

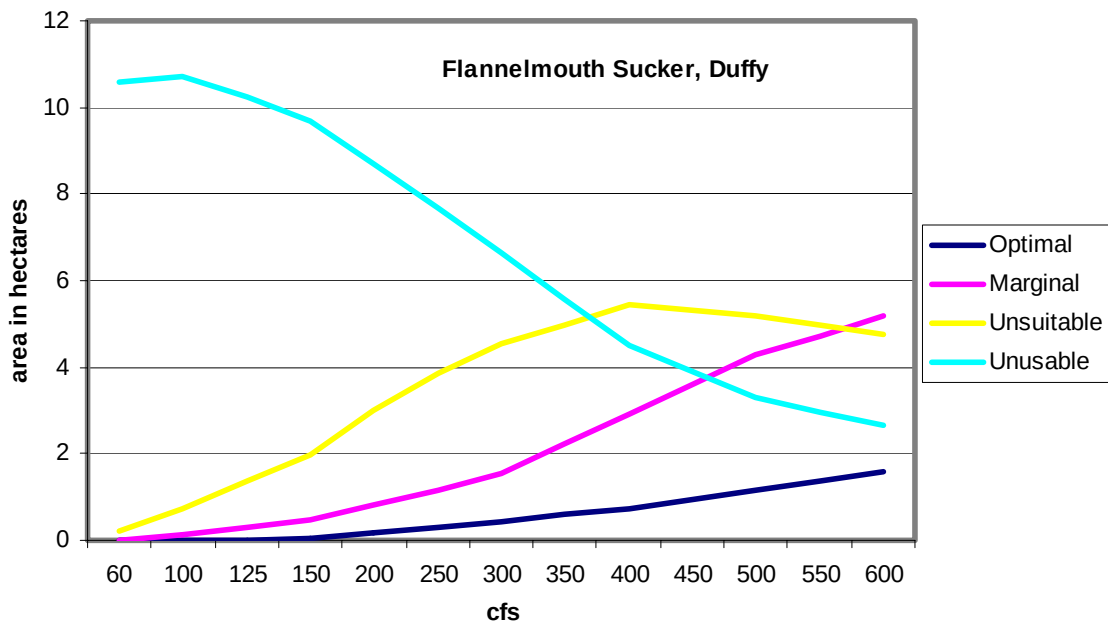


Figure 21. Flannemouth sucker habitat availability at Duffy, Yampa River.

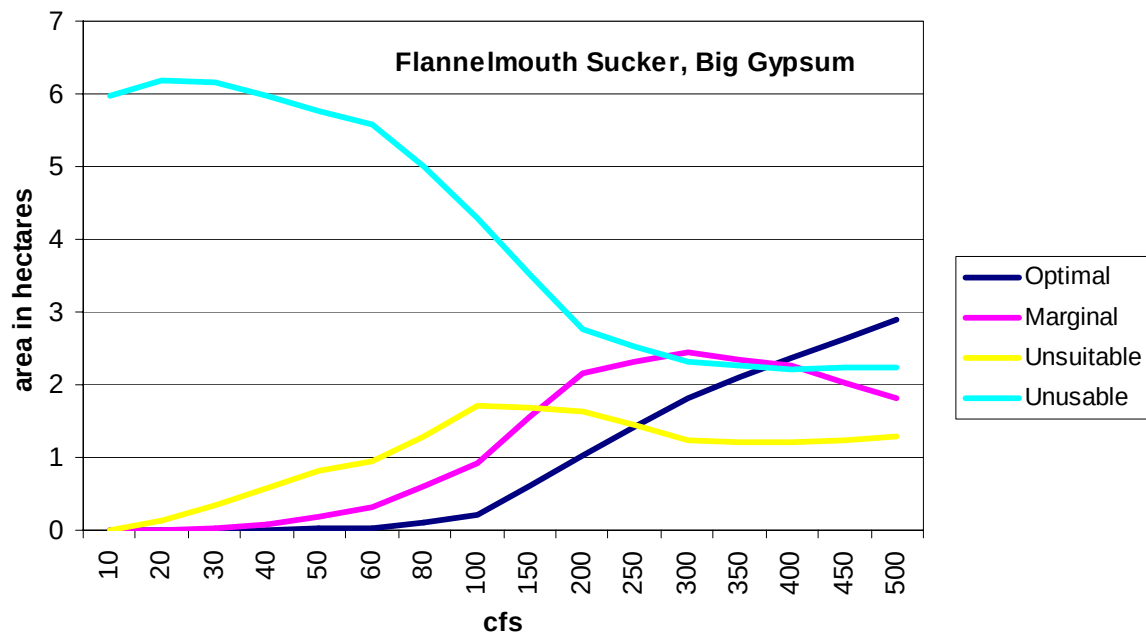


Figure 22. Flannemouth sucker habitat availability at Big Gypsum, Dolores River.

Big Gypsum had a higher total biomass per hectare for all sites at a given flow due to its smaller channel. The slope of the flannemouth biomass increased slowest from 10 to 60 cfs and the increase was fastest from 60 cfs to 150 cfs. At 150 cfs, the adult flannemouth biomass was 150 kg/ha (Figure 23). Below 80 cfs the Big Gypsum site had less than 5 kg/ha. Big Gypsum had a higher projected flannemouth biomass than the Colorado River. At 400 cfs, the projected biomass at Big Gypsum was 250 kg/ha, compared to 225 kg/ha and 200 kg/ha at flows of 1800 cfs at Corn Lake and 2000 cfs at Clifton respectively. Typically base flows are less than 60 cfs on the Dolores River. At 60 cfs, flannemouth biomass was about 31 kg/ha and about 23 kg/ha at 50 cfs.

Corn Lake had the highest projected biomass for flows between 250 cfs and 500 cfs (Figure 23). At base flows of near 1000 cfs, biomass at Corn Lake was projected to be near 210 kg/ha. There was an inflection of the biomass curve at Corn Lake at 500 cfs. Above 500 cfs the biomass curve increased at a lower rate.

The **Clifton** site had the lowest adult flannemouth biomass curve for flows over 300 cfs (Figure 23). Flows over 1000 cfs did not increase habitat potential for adult flannemouths. The adult flannemouth biomass curve for the entire 15-Mile Reach was likely intermediate to that found for Corn Lake and Clifton. Corn Lake was found to have a below-average mean width and Clifton had an above-average mean width. We defined Mean width as a geomorphic feature influencing velocities. Velocity strongly influenced habitat suitability. Corn Lake represented the upper limit and Clifton the lower limit regarding to flannemouth habitat potential in the 15-Mile Reach.

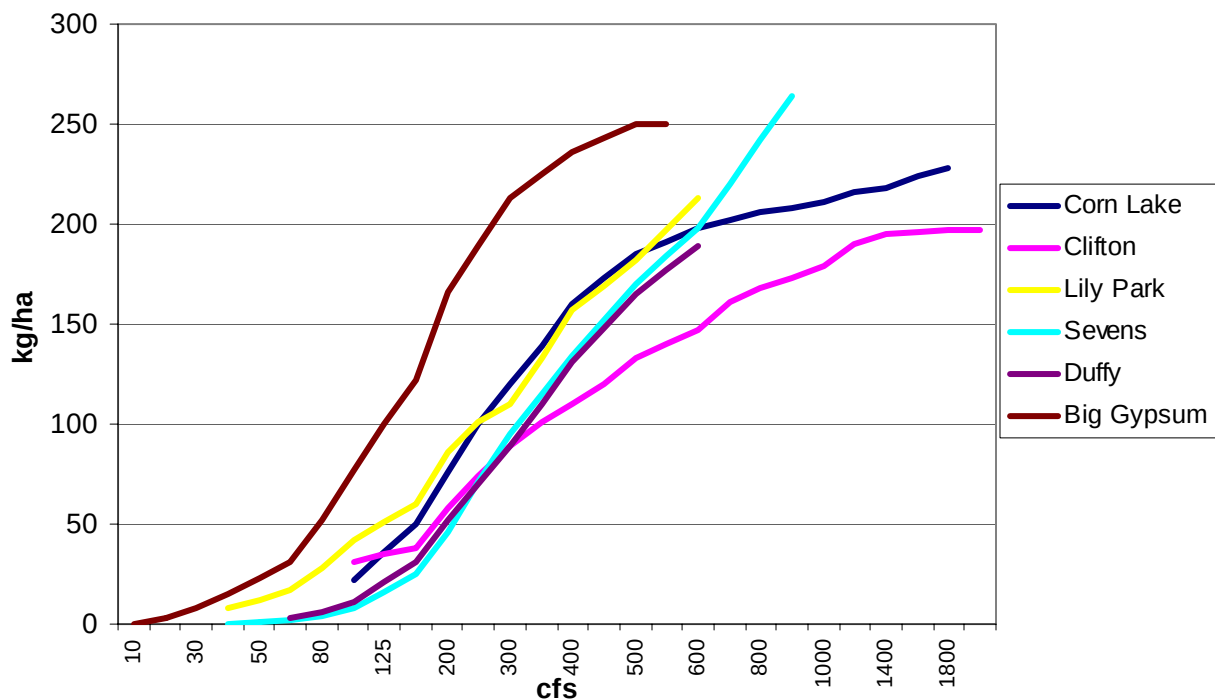


Figure 23. Project flannemouth biomass as a function of flow for all study sites.

The **Lily Park** site had the highest potential for flannemouth habitat at flows less than 200 cfs (Figure 23). The geomorphic characteristics that stood out at Lily Park were the narrower channel, higher bed slope and larger sediment size. The narrower channel and higher bed slope resulted in higher depths and velocities at lower flows. Corn Lake had a very similar projected biomass compared to Lily Park at flows from 150 to 500 cfs, indicating similar geomorphic characteristics between the sites. These data also suggested that given similar flow scenarios, the flannemouth populations would be similar for these sites.

Sevens and **Duffy** have nearly identical flannemouth curves for projected biomass (Figure 23). The geomorphology of these sites was similar with a lower bed slope and a wider wetted width in the lower flow range (>600 cfs). At about 600 cfs, biomass potential, based on the availability of the four functional meso-habitat types was nearly identical at the Sevens, Duffy, Lily Park and Corn Lake sites. At flows over 600, optimal velocities were being exceeded at Corn Lake and the curves flattened out. But at Sevens and Duffy, it appeared that flows of 400 cfs to 600 cfs were required to achieve the velocities that produced optimal habitat.

The projected biomass for the 60-day low flow was regressed against the measured biomass for all stations for which data was available except for Duffy. Duffy was excluded because pure flannemouths are very rare at this site, a condition due to hybridization and predation, not due to habitat availability.

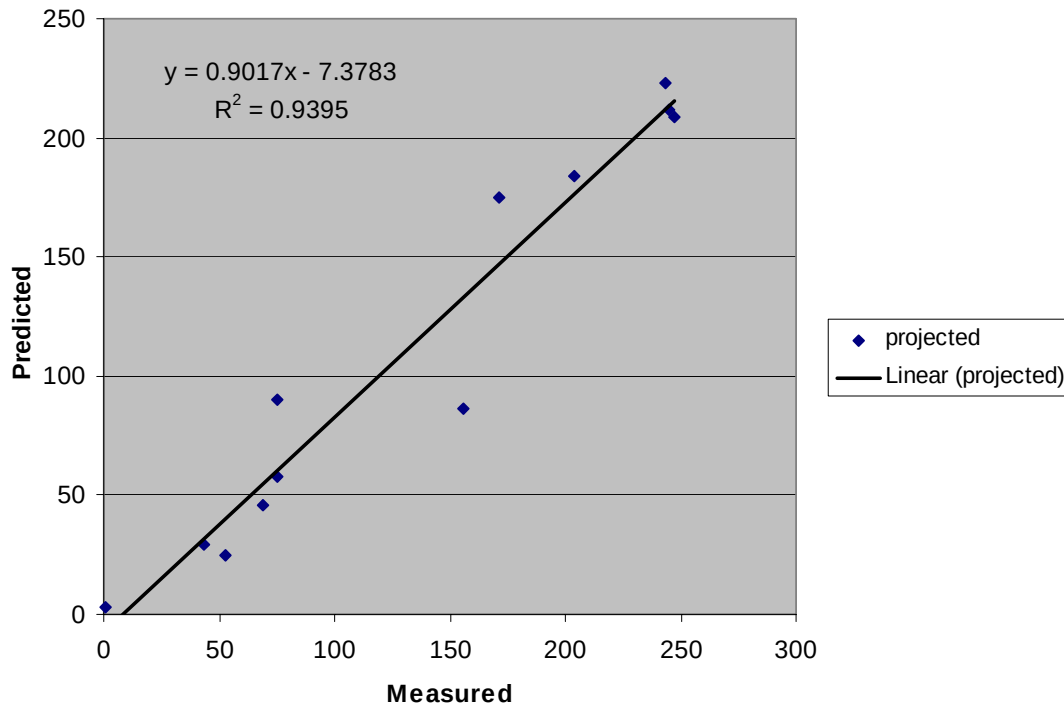


Figure 24. Projected versus observed flannemouth sucker biomass for five study sites

DISCUSSION

Habitat Modeling, Flow Needs for Native Sucker

This study established baseline fishery data at six study sites and used this data to develop habitat suitability criteria and model validation. Another value of the fishery data was that it established consistency in the fish community through time. Consistency in community structure within each site strongly suggested a dynamic relationship among the sites' habitats. Consistency in fishery characteristics also promoted confidence that habitat modeled in one year not only represented both the geomorphic and fishery aspects for that time period, but that it also represented conditions through time.

The 2-D flow modeling quantified habitat conditions at each study site so that habitat availability could be directly correlated to fish biomass. The main variable of habitat availability was flow. Differences in habitat appeared to explain several differences in fish community composition and biomass among sites and between rivers. A significant correlation was found for the six study sites between habitat availability and abundance of the native blueheads and flannelmouths. The two sites in the 15-Mile Reach had the highest base flows, the highest optimal habitat availability and the highest density and biomass of total fish and native fish. Lower base flows and lower native sucker habitat and biomass were found at Sevens, Duffy and Big Gypsum.

Both blueheads and flannelmouths were found to have strong preferences for habitats with minimum velocities of above 0.5 m/s. In the Colorado River, habitats with currents over 0.5 m/s were abundant in the flow range of 800 to 1000 cfs. In the Yampa River base flows were typically less than 250 cfs and lower velocity runs were the dominant habitat between flows of 150 to 250 cfs.

Because a significant relationship was found between available habitat and bluehead and flannelmouth biomass, species abundance was used as a relative indicator of the habitat abundance. In the 15-Mile Reach, blueheads and flannelmouths had similar species composition and similar amounts of habitat availability. In the Yampa River flannelmouth biomass and habitat was much higher than it was for blueheads.

Bluehead population estimates made in 2000 and 2001 in the 15-Mile Reach were near 1200 fish per km and 100 kg/ha. Anderson (1997) reported fishery population data for three sites upstream of the 15 Mile-Reach. Species composition (30 to 37%), length-distribution and density estimates (90 to 97 kg/ha) made for blueheads near Una and Parachute were very similar to that in the 15-Mile Reach. Generally, flows during the irrigation season (April to November) were considerably higher upstream of the Roller Dam due to the amount of water that was being diverted (1200 to 1600 cfs). Bluehead sucker standing stocks were similar above and below the Roller Dam. That indicated similar habitat quality despite less flow in the 15-Mile Reach. The 2-D habitat analysis found only minor increases in bluehead habitat availability when flows increased above 1400 cfs.

Osmundson (1999) reported catch rates of blueheads (fish per minute of electro-fishing) in the Colorado River from samples made in 1994 and 1995. The catch rate in the 15-Mile Reach, Strata 9 (2.2 fish/min) was higher than upstream of the Roller Dam at Strata 10 near Una Bridge (0.8 fish/min) and at Strata 11 at Parachute (1.5/min). Osmundson's fishery data indicated blueheads were more numerous in the 15-Mile Reach. This suggested bluehead habitat availability was also greater, even with reduced flows compared to above the Roller Dam.

The flannemouth estimates made in 2000 and 2001 in the 15-Mile Reach were approximately 1600 fish per km and 220 kg/ha. These estimates were very similar to Anderson's (1997) reported density estimate of about 1750 flannemouth / km at Parachute in 1994 and 1995. The flannemouth biomass of 185 kg/ha (Anderson 1997) was lower than found in this study because it was calculated using mean channel width and not wetted width. Species composition of flannemouths in the 15-Mile Reach was also similar to Parachute (34 to 40%) (Anderson 1997). The 2-D modeling found increasing flannemouth habitat with increasing flows up to about 1200 cfs. Therefore, much higher flows at Parachute apparently have not resulted in a much larger population size of the flannemouth.

Fish sampling data in the Colorado River from 1994 and 1995 by Osmundson (1999) found flannemouth catch rates were highest in the 15-Mile Reach. Flannemouth catch rates in Strata 9 or the 15-Mile Reach were about 1.6 fish/min compared to about 0.5 fish/min at Strata 10 (Una Reach) and about 1.2 fish/min at Strata 11 (Parachute) (Osmundson 1999). Osmundson's fishery data was fairly consistent with Anderson's (1997) and corroborated the 2-D modeling data that found that maximum flannemouth habitat was provided by flows of 800 to 1200 cfs.

The 2-D habitat modeling showed that the 15-Mile Reach appeared to be near the carrying capacity of habitat for adult blueheads and flannemouths in the flow range experienced during the study period (800 to 1000 cfs). The fishery data showed an abundance of juvenile blueheads and flannemouths indicating habitat for smaller fish (<15 cm) was also available. Both the habitat modeling and the fishery data indicated that habitat for these native fish was not limiting or problematic.

Pitlick and Cress (2000) found that the Colorado River near Una and Parachute had a slope and bankfull width very similar to the 15-Mile Reach. Given similar channel morphology (width and slope) at particular sites, modeled habitat availability was also similar. Therefore the meso-habitat curves and flow recommendations determined for blueheads and flannemouths in the 15-Mile Reach most likely were transferable to above the Roller Dam, since channel characteristics were similar.

Discharge (Q) equalled width x mean depth x mean velocity, so the same flow in a narrower channel meant either depths or velocities were increased. This was obvious at the Big Gypsum site, which had the narrowest stream width and was able to provide higher optimal bluehead habitat at lower flows. For the large rivers, Corn Lake had the

narrowest width for flows less than 600 cfs and had the highest percent of optimal bluehead habitat in the lower end of the modeled flows.

Other geomorphic features such as bed slope directly influenced mean depths and velocities. Sevens and Duffy had the lowest bed slopes of the study sites and the highest percentage of Unusable native sucker habitat at flows less than 400 cfs. Lily Park had the highest bed slope and maintained habitats with swifter currents at lower flows than did Sevens and Duffy. Higher bed slope and a narrower width likely explained the higher fish productivity at Lily Park compared to Sevens and Duffy.

The 2-D habitat model showed that Sevens and Duffy required a flow of 400 cfs to yield an equal amount of bluehead habitat as Corn Lake at a flow of 250 cfs. This was partially due to Sevens and Duffy being wider than the Colorado River sites. The Colorado River was a larger river than the Yampa in terms of drainage area and mean annual flow. The drainage area at the Cameo gage (Colorado River) was 8050 square miles. Mean annual flow was 3897 cfs and median peak flow was 17900 cfs (68 years). For the Yampa River Maybell gage (86 years), the drainage area was 3837 square miles, the mean annual flow was 1568 cfs and the median peak was 9880 cfs (86 years).

Piktlick (1999) reported the Colorado River channel had narrowed slightly and was more or less in equilibrium with the present flow and sediment transport regimes. Pitlick (1999) also found that, in general, base flows in the Colorado River were somewhat higher than natural base flows. The Yampa River likely had the reserve conditions. The channel upstream of Cross Mountain appeared to be unstable as indicated by a poor riparian zone along most of the river. Also current base flows were greatly reduced, primarily for irrigation use, compared to pre-development flows (CWCB report, <http://cdss.state.co.us>)

The 2-D habitat model appeared to be in sync with fishery data collected under a variety of flow conditions. The Yampa River represented fishery data from a community exposed to lower flow conditions than in the 15-Mile Reach. The Lily Park site had similar channel widths and slopes as the 15-Mile Reach, so differences in habitat availability were mainly due to the flow differences. Also, the first two years of fishery data at Sevens and Duffy were collected when summer flows were near 250 cfs (1998 and 1999), but flows were noticeably less during the second two years (2000 and 2001).

Sevens and Duffy had about 20% of the bluehead habitat at a flow of 250 cfs. Sevens had about 21% of the biomass of the 15-Mile Reach (900 cfs). Lily Park (250 cfs) had about 28% of the projected habitat availability and had 39% of bluehead biomass as the 15-Mile Reach (900 cfs). The 2-D model for Duffy (250 cfs) indicated that bluehead habitat availability was much higher than reflected by the existing biomass, which was likely depressed by predation and hybridization (Anderson 2002). The 2-D modeling results indicated that bluehead sucker biomass in the 15-Mile Reach would decrease to about 20 to 40% of the current conditions if 250 cfs were to become the long-term mean flow.

At Lily Park, the flannelmouth density estimate was very similar to the 15-Mile Reach (near 1670/km), but Lily Park's flannelmouth biomass was 64% of that at Corn Lake. It appeared that the higher gradient at Lily Park was beneficial for maintaining flannelmouth numbers at the lower flows. Biomass was less at Lily Park because large flannelmouths were less frequently captured at Lily Park. At Lily Park, 42% of flannelmouths were larger than 40 cm and 3% were over 45 cm, but at Corn Lake 73% were larger than 40 cm and 30% were over 45 cm. Apparently, the shallower and slower habitats at Lily Park were not suitable for supporting the larger-sized adult flannelmouths.

The difference in size structure was even more pronounced at the Dolores River site, where the largest flannelmouth collected was 31 cm. This differential in size was also observed for both blueheads and roundtail chubs with there being high numbers of larger-sized fish at Corn Lake, fewer larger fish in the Yampa and even fewer in the Dolores River. Differences in fish size were observed at Sevens between the higher and lower flow periods for blueheads. During the relatively high flow year of 1999, 83% of blueheads were over 30 cm and 29% were over 35 cm. This was 45% over 30 cm and 9% over 35 cm during the low-flow year of 2001. Mean lengths of blueheads were high at Duffy because fish under 35 cm were likely removed by predation during the study period (Anderson 2002).

The lack of larger-sized (>35 cm) fish in a population was probably due to lack of adult fish habitat, which was likely an attribute of poor flow conditions. The fish community of the Dolores River in 2001 consisted mostly of blueheads and flannelmouths sucker less than 20 cm. The lack of adult-sized fish clearly indicated a lack of adult fish habitat for these species.

Habitat Composition and Diversity

Regressions between habitat and fish productively were significant among the six study sites. In general it appeared that sites with high amounts of riffle habitat had higher total fish biomass and higher bluehead biomass. Riffles were the primary meso-habitat for most aquatic macroinvertebrates. The availability of riffle habitat was a good indicator of general productivity of a river.

Sites with higher amounts of deep-run and deep-pool habitats had higher amounts of catfish, carp and white suckers. Not all species, however, displayed a direct relationship between biomass and a meso-habitat type (roundtail chub). Also, with only six study sites in the project, sample size was rather small for an in-depth analysis. Other factors such as variability in predation and hybridization rates between sites could not be included in a regression analysis. But even given these factors the analysis indicated habitat was a major influence on native fish biomass and composition.

The Shannon-Weaver diversity index provided a means of comparing habitat complexity at each study site, with higher habitat diversity suggesting improved conditions for maintaining fish community diversity. Habitat diversity (Shannon-Weaver) peaked at 1000 cfs at Clifton and at 1200 cfs at Corn Lake. Maximum meso-habitat diversity occurred in the same flow range that produced maximum habitat for adult native suckers. Flows of 1000 to 1200 cfs were also the near the flows when fish were sampled, and numerous age-0 and age-1 native suckers, roundtail chub and speckled dace were collected. These collections of young fish also indicated 1000 to 1200 cfs resulted in suitable habitat all life stages.

Since flows were not modeled above 600 cfs for the Yampa River the flow associated with peak habitat diversity was not identified. However, at 600 cfs Lily Park had the greatest habitat complexity (2.22) followed by Sevens (1.92) and Duffy which had the least complex habitat (1.73). This order of habitat complexity matched the order of fishery diversity found on the Yampa River. The consistency in species composition and size structure observed at Sevens and Duffy from 1998 to 2000 was not maintained in 2001 when flows and habitat complexity were less.

Field Observations, Flow Needs of Native Fish

There were some field observations made at Lily Park during electro-fishing that confirmed some of the 2D habitat modeling results for the Yampa River. In 2000 there was a large difference in flows between field trips (Anderson 2001). During trips when flow was less than 120 cfs, flannelmouths were collected from backwater habitats that were not occupied at flows above 120 cfs (Anderson 2002). These observations showed that flannelmouths were compelled to occupy non-preferred habitats when flow was less than 120 cfs. The electro-fishing raft had to be dragged in Lily Park at flows less than 120 cfs and during these occasions it was observed that fish were confined to the deepest remaining water pockets. The concentration of large numbers of fish in shallow and confined habitats made them highly vulnerable to capture by us, avian and terrestrial predators.

Anderson (2002) reported a dramatic decline in two native fish species in the Yampa River fish community in 2001. The speckled dace and the mottled sculpin were both common in 1998 and 1999 at Duffy and Sevens. Both are small-bodied fish that occupy shallow habitats. Small-bodied fish should be less susceptible to population crashes during low flow events, and these fish likely could have maintained viable populations if low flows were the only factor. The Dolores River population was comprised mostly of native species, but the vast majority were small, less than 20 cm length. The Dolores River did not have the same burden of nonnative predators as the Yampa River.

The disappearance of dace and sculpin in the year 2001 was concurrent with an increase in the number of smallmouth bass. Anderson (2002) considered the shifts in these species to be connected. As flows fell below a certain threshold (as experienced in both 2000 and 2001), velocities were reduced in virtually all riffles making them suitable

habitat for YOY smallmouth bass. YOY bass were not observed in riffles during the field surveys in 1998 and 1999. This shift in species composition occurred during years when stream flow was less than 120 cfs for most of the summer. When riffle habitats were unsuitable to maintain small-bodied fish like speckled dace, they become unusable for large-bodied fish like blueheads.

Speckled dace on the Colorado River were found to comprise 72% of the catch from shallow riffles (Miller et al. 2003). The next most common fish in riffles were sand shiners at 9%, juvenile flannelmouths 6% and juvenile blueheads were 3 percent (Miller et al. 2003). Miller et al. (2003) made density and biomass estimates for small-bodied fish in the 15-Mile Reach using depletion sampling. Their estimate for speckled dace was 2.36 dace per meter square of riffle. This value multiplied by the area of riffle meso-habitat from the 2-D modeling at 1000 cfs for Corn Lake and Clifton resulted in a projected speckled dace density over 15000 dace/km in the 15-Mile Reach. If 2.36 dace/km is somewhat valid for the Yampa River riffles, based on riffle habitat area at 200 cfs, the projected speckled dace numbers 4500/km at Duffy, 1200/km at Sevens, and 4000/km at Lily Park. The speckled dace population dropped at 100 cfs to 856/km, 218/km and 1300/km for Duffy, Sevens and Lily Park respectively. Speckled dace numbers for 60 cfs were projected only for 196/km, 23/km, and 196/km at Duffy, Sevens and Lily Park respectively.

The roundtail chub was another large-bodied native fish that we attempted to model by determining its meso-habitat suitability. Significant correlations were not found between roundtail chub biomass and a meso-habitat type that could be defined by depths and velocities. Roundtail chub was a predator that occupied deep pools during the day and moved through several habitats to forage in the evening (Byers 2001). The roundtail chub, therefore, was a multi-habitat species that was found in the habitat it occupied at the time of the fish sampling. Stewart (2000) proposed an approach to characterize an analysis of adult chub habitat using habitat complexity indices such as richness and evenness. The approach was still under investigation at the time of this report, and will be examined further in the next project cycle.

The fish community of the Dolores River appeared to be highly stressed. Species composition of native fish was high, but most fish were small. Roundtail chub was the most common species and biomass was very low. These attributes appeared to be habitat and flow related. The lack of runoff flows in 2000 and 2001 may have negatively impacted productivity. Riffles and runs had large silt deposits and both forage and habitat potential seemed unnaturally low. If the Colorado River data can be used as an example of a high-quality habitat and fishery, the Dolores River data can be useful as an example of very poor quality habitat conditions. The lack of non-native piscivores, like smallmouth bass, apparently allowed young and small fish survival, but clearly there was a lack of habitat for larger individuals. Even the channel catfish was affected.

Since the construction of McPhee Reservoir, the spring runoff flows have been greatly modified. Mean monthly flows from 1985 to 2001, from the Bedrock gage, for May and June were about half of flows during the period prior to 1985. The loss of spring

runoff flows, as in the Dolores River below McPhee Reservoir, appeared to be causing channel downsizing and heavy siltation deposits. A more natural native fish community would be possible in the Dolores River if a natural shape was restored to the hydrograph.

Non-Native Fish Versus Flows

The 2D habitat modeling data suggested a relationship between habitat availability, and composition and of abundance of nonnative fish. On the 15-Mile Reach common carp were the most prevalent nonnative species and channel catfish and white suckers were fairly uncommon at about 5 to 6% of the total fish over 15 cm. Common carp and white sucker were collected, primarily in backwater and deep shoreline habitats, suggesting that faster mid-channel habitats were not suitable for these species.

On the Yampa River, white sucker and roundtail chub were very rare at Lily Park. This may have resulted from a lack of reproductive and nursery habitats in this high gradient site. White suckers were very common in the Yampa River upstream of Maybell. Elmlad (2003) reported that ISMP sampling found 50% of the catch at Maybell were white suckers. This species was 62% of the catch in the Juniper area. At Duffy about 70% of the fish collected were white suckers prior to 2001. The slow flowing (pool) habitats of Duffy appeared to be ideal for all life stages of this species. In contrast, the Dolores River is an example of a river with primarily slow flowing habitats, but has no white suckers. Without white suckers in the Yampa River, native sucker species could likely maintain a much stronger presence.

White suckers and its hybrids with flannelmouths and blueheads were examined on the Yampa River in the mid 1970's. About half of the white suckers examined in the field were identified as hybrids with native sucker species (Prewitt (1977)). White x flannelmouth and white x bluehead hybrids were more successful than pure native suckers in the river upstream of Maybell. This may have been a function of habitat or possibly the white sucker hybridization imparted better predation defenses, as it co-evolved with the nonnative piscivores present in the Yampa River.

Results of the four years of sampling on the Yampa and 3 years on the 15-Mile Reach strongly indicated that the magnitude of base flows was critical for maintaining a strong native fish community. It was established that native fish prefer higher velocity habitats and that nonnative fish exhibit a preference for lower velocity habitats. Backwater and shallow pool habitats had higher composition during low flow. Sunfish and white sucker populations were increased during lower base flow years. The negative impacts of smallmouth bass were less in 1998 and 1999, the years that had higher base flows. Smallmouth bass had a much higher presence at Duffy and Lily Park in 2001 than at Sevens. The lower numbers of bass at Sevens suggested that habitat was less suitable for smallmouth bass at that site.

Flows during the irrigation season may be more important for minimizing non-native nuisance species than flows during the runoff. Large numbers of smallmouth bass YOY were observed in 1998 and 1999 when runoff flows were near 10,000 cfs. It appeared that normal high runoff flows did not negatively impact this species. It will take more years sampling to provide empirical data that will help determine the relative importance of base flows versus peak flows.

Anderson (2002) speculated that Cross Mountain Canyon was a barrier to fish passage at the flows observed in the summer of 2000. Fish passage in Cross Mountain Canyon could be problematic for migrating species, e.g., channel catfish and Colorado pikeminnow at flows of less than 100 cfs.

Hawkins et al. (1997) found a low occurrence of nonnative fish in the Little Snake River during a period when flows were near zero, but did not provide data about species composition during normal flow years. Hawkins et al. (1997) suggested that native species may be more tolerant of drought flows and therefore had an inherent advantage under such condition over non-native species. The fishery data from the Little Snake and Dolores Rivers appeared to be similar. There was a high native fish composition during very low flows. The Dolores River fish community appeared to be highly stressed and unnatural. In the Yampa River, native fish versus nonnative composition varied among sites. This indicated habitat availability was also important for non-native species as well as natives.

On the Colorado River, the Clifton site had more total area than Corn Lake, but it was entirely in pool and backwater habitat. The higher availability of pool and backwater habitat was primarily utilized by nonnative species (largemouth bass, green sunfish, carp) and somewhat by juvenile native fish (i.e. roundtail chub), but not by adult native fish. Reduced flows in the 15-Mile Reach increased unusable habitat for native fish and suitable habitat for nonnative species.

Flows for Endangered Fish

Flow recommendations by the Recovery Program were much different for the Yampa and Colorado Rivers. The Recovery Program recommended a mean monthly flow of 1243 cfs during the irrigation season for an average year for the 15-Mile Reach to maintain habitat for adult Colorado pikeminnow (Osmundson 1996). The flow recommendation for the Yampa River was to maintain 93 cfs at the historic frequency observed at the Maybell gage (Modde et al 1999), i.e., the frequency of flows less than 93 cfs were not to increase compared to gage records. The contrast in flow recommendations was quite dramatic given that life history and habitat needs of endangered fish should be similar regardless of the specific river.

The fishery data and the 2-D modeling results did not indicate habitat problems for non-endangered native species in the 15-Mile Reach. The 2-D modeling found that similar flows provided similar habitat availability for adult native suckers in the Colorado and Yampa Rivers. We interpret these results to indicate that habitat availability for adult

endangered species was not likely problematic in the 15-Mile Reach. The availability of prey fish (10 - 30 cm) appeared high in the 15-Mile Reach suggesting that forage availability was not lacking for adult Colorado pikeminnow (Osmundson 1999). In spite of seemingly good habitat and forage, the numbers of endangered fish collected in this study and by recent recovery program efforts have been very low in the 15-Mile Reach.

Catch rate and population estimate data suggested that Colorado pikeminnow had similar population sizes in the Colorado and Yampa Rivers during the period of 1987 to 2000 (McAda 2002 and Osumndson 2002). The fact that Colorado pikeminnow densities were similar for the Colorado and Yampa River further suggested that neither habitat nor forage availability has limited pikeminnow abundance in the 15-Mile Reach. The bottleneck for Colorado pikeminnow and razorback sucker in the Colorado River was most likely related to reproduction and recruitment (Osmundson and Kaeding 1991). Colorado pikeminnow reproduction occurred during the descending limb of the hydrograph and lack of recruitment was linked with predation of larvae (Bestgen 1997). Data from this study indicated that YOY smallmouth bass appeared to be an efficient predator of fish larvae in the Yampa River. If YOY smallmouth bass become prevalent in Dinosaur Canyon, this could have a major impact on survival of Colorado pikeminnow larvae.

FLOW RECOMMENDATIONS

The intent of this project was to develop flow recommendations that would be adequate to provide suitable flows for maintaining existing populations of native fish. The first three years of the project were spent documenting the status of existing native fish populations in the 15-Mile Reach of the Colorado River, the Yampa River and the Dolores River. The fish population data was necessary to create the habitat suitability criteria and also to provide baseline population data given existing habitat conditions.

The habitat analysis found several similarities in channel morphology, suitability curves and flow/habitat relationships between the Yampa and Colorado Rivers. The data also strongly suggested the Yampa and Colorado Rivers would have similar native sucker populations given similar instream flow scenarios. Flow recommendations for these two rivers, however, were not similar because of large differences in historical flows and water availability.

Colorado River

The base flows in the 15-Mile Reach in 2000 (900) and 2001 (1000) were found to be near optimal in providing suitable for habitat for native suckers and in maintaining habitat diversity. Neither the fish sampling data nor the habitat modeling results gave indications that flows above 1200 cfs would improve habitat conditions or biomass of native sucker species. Base flows observed in the Colorado River in 2000 and 2001 appeared suitable to maintain the existing native fish population for the long term.

The 2-D habitat model showed that bluehead habitat and projected biomass falls rapidly when flows drop below 600 cfs, and at 200 cfs or less habitat availability and predicted biomass is very low compared to current estimates. Base flows of 600 to 800 cfs appear sufficient to maintain the bluehead sucker population size found during the study period.

Pitlick (1999) reported that base flows in the Colorado River were slightly higher than native flow. For the historic record, flows less than 800 cfs have been uncommon in the 15-Mile Reach (Osmundson and Keading 1991), establishing a history of near optimal habitat conditions. We recommend that optimal habitat be sustained. The 2-D habitat modeling data indicated that a mean monthly flow of 650 cfs during the late irrigation season (July 1 to October 31) would likely maintain native sucker species at or very near the existing population size. A mean monthly flow of 650 cfs would be achieved if flows exceed 400 cfs for 100% of the month, exceed 525 cfs for 25% of the month and exceed 650 cfs for 50% of the month. To simplify the recommendation to a single flow, 600 cfs should be considered the instream flow recommendation for the Colorado River in the 15-Mile Reach.

Yampa River

The Tennant Method (Instream Flow Council 2002) calculates a minimum flow of 465 cfs as a recommendation for the Yampa Rivers' mean annual flow of 1552 cfs. Base flows over 300 cfs have been uncommon in the Yampa River during the irrigation season even though 300 cfs seems fairly low for a river the size of the Yampa. The median minimum flow for the Maybell gage was only 121 cfs. Both fish observations and habitat modeling identified that flows less than 120 cfs do not provide enough habitat to adequately support native fish.

The goal for flow management on the Yampa River is to provide enough flow to avoid degraded habitat (unsuitable depths and velocities in riffles and runs). The fish sampling data found conclusively that summer flows during 2000 and 2001 had negative impacts on the native fish populations of the Yampa River. The recovery time frame of native fish (speckled dace, mottled scuplin and bluehead sucker) is unknown at this time since flows in 2002 were even lower. Base flows of 1998 and 1999 were found to sustain native fish. It is recommended that the flow conditions of these years be used to model for instream flow scenarios in the future.

Compared to the Colorado River the Yampa River upstream of Cross Mountain Canyon appears overly-wide and the channel is unstable. Improved riparian management and activities that promote bank stabilization and a more natural-sized channel would have long term benefits for native fish in the Yampa River. Also, base flows on the Yampa River are much reduced compared to native flow.

The 2-D meso-habitat model found that flows below 200 cfs appear to be highly problematic for blueheads on the Yampa River. It appears that base flows need to be over 400 cfs to have a significant improvement in bluehead habitat at all three sites. In regard to blueheads, it appeared flows less than 200 cfs should be avoided.

A minimum flow of 200 cfs is necessary to maintain native fish at the levels observed in 1998 and 1999. A monthly average of 200 cfs would likely avoid severely degraded conditions. To achieve this standard it is recommended that flows exceed 120 cfs for 100% of the month, exceed 150 cfs for 25% of the month and exceed 200 cfs for 50% of the month. If a single flow is desirable then the instream flow recommendation is 175 cfs.

Dolores River

The Dolores River was found to have a high species composition of native fish, but very poor size structure and biomass. In fact, the fishery of the Dolores River in Big Gypsum was so poor it has become an example of a fish community representative of extremely altered flows and habitat. The Dolores River has the potential to be an important river for native fish management given adequate instream flows. Habitat modeling found that flows of 200 cfs would maintain riffle habitats. Base flows of this magnitude would likely result in a fish density and biomass similar to estimates in the 15-Mile Reach. However, it does not appear likely that flows of 200 cfs are available.

Perhaps an even larger problem than base flows is the change in runoff flows. There has also been a lack of peak or flushing flows in the Dolores River during the study period. The lack of flushing flows appears to have severely reduced productivity of this river. The 2-D modeling suggests an instream flow of at least 80 cfs. The field data suggests a runoff flow of near 1200 cfs, but more modeling is needed for this river.

SUMMARY

Four years of fish population characteristics were summarized at Sevens and Duffy on the Yampa River. Density, biomass and size structure in the first two years 1998 and 1999 were higher than in 2000 and 2001. We examined the fish data at Lily Park in 2000 and 2001. We attributed the observed changes in the fishery at Sevens and Duffy to poorer flow and habitat conditions in 2000 and 2001. Low flows appeared to be responsible for negative impacts to blueheads, speckled dace, mottled scuplin, flannelmouths, white suckers and channel catfish. Smallmouth bass and sand shiners appeared to respond positively during the lower flow years on the Yampa.

Three years (1999, 2000 and 2001) of fish population characteristics were summarized at Corn Lake in the 15-Mile Reach and two years (2000 and 2001) of fish data were collected at the Clifton site. Density, biomass and size structure of the native fish community appeared to be at carrying capacity and representative of an ideal population.

Two years (2000 and 2001) of fish population characteristics were summarized at the Big Gypsum site on the Dolores River. Although native fish species composition was high in both years, fish density, biomass and size structure were considered to be fair in 2000 and very poor in 2001. The Dolores River fishery appeared to have a highly stressed and unnatural fish community and served as an example of a population in a highly degraded habitat.

We observed two-dimensional habitat modeling at all sites with fishery data. We developed meso-habitat suitability curves based on fish distribution within each site. Meso-habitat suitability were validated and used to project habitat availability for a range of simulated flows. Geomorphic characteristics were similar for the Yampa River and Colorado in the range of flows modeled. Habitat for flannelmouth and bluehead suckers were maximized or optimal at flows near 1000 to 1200 cfs for the Colorado. The 1000 to 2000 cfs flows were likely the optimal flows in the Yampa River, but the flows were not modeled over 600 cfs. Flows less than 400 cfs provided significantly reduced habitat for flannelmouth and bluehead suckers. Nearly 100% of available habitat was in the unusable category for flannelmouth and bluehead suckers at flows of 100 cfs and less.

We made instream flow recommendations based on the 2-D meso-habitat modeling and observations made during the fish sampling. To maintain the existing population in the 15-Mile Reach instream flows should exceed 600 cfs. A instream flow target for the Yampa River is 200 cfs and flows less than 120 cfs need to be avoided to prevent loss of riffle-habitats. Instream flows of 60 to 80 cfs may be sufficient to maintain a native fish community in the Dolores River, as long as runoff flows are provided in the spring. The lack of spring flows in the Dolores River appears to have severely reduced the fishery potential there.

CONCLUSIONS

- 2-D habitat modeling found that flows of the same magnitude provide about the same amount of habitat availability for both the Colorado and Yampa Rivers.
- 2-D habitat modeling found the Yampa River had a larger stream width at flows less than 600 cfs even though the Colorado River had the larger drainage area and mean annual flow.
- Flows (900 to 1000 cfs), habitat availability and the non-endangered native fish community in the 15-Mile Reach documented during the study period were all found to be representative of near ideal conditions.
- Flows above 1200 cfs on the Colorado River do not enhance habitat availability for adult native suckers.
- Flows below 400 cfs will likely result in significant reductions in density and biomass of flannemouths and blueheads in the 15-Mile Reach.
- The present flow management strategy for the 15-Mile Reach is to maintain historic flows and optional habitat conditions. Flows of 600 to 800 cfs will provide suitable habitat to maintain the existing native fish population in the 15-Mile Reach.
- Flows, habitat availability and the non-endangered native fish communities in the Yampa River documented during the study period were poor compared to their potential and to the 15-Mile Reach.
- Flows less than 120 cfs do not provide suitable habitat for adult native suckers and should be avoided.
- Flows of 300 to 400 cfs are required to provide suitable habitat for a healthy native fish population at the Yampa River.
- The flow management strategy for the Yampa River is to avoid severe habitat degradation. An instream flow of 200 cfs should be considered the minimum flow for the Yampa River.
- The Dolores River was sampled under similar base flow for two years, but the fish population was much degraded in the second year. Lack of peak flows appears to have caused the negative impact on the native fish population of this river.
- For the Dolores River an instream flow of 80 cfs and a minimum runoff flow of 1200 cfs are recommended. Further study is required on the Dolores River.

RECOMMENDATIONS FOR FUTURE FLOW RESEARCH

1. Reform model flows for the Yampa River 2D sites up to 2000 cfs as was done for the 15-Mile Reach. This is needed to complete modeling habitat suitability and habitat diversity.
2. Continue working with Dr. Richard of Mesa State College to determine channel geomorphology. Conduct a channel geomorphic study for the Yampa River to determine bankfull flows and channel stability. Also, summarized flow records are needed to determine the scale in reduction of base flows on the Yampa River.
3. Survey the floodplain of the Dolores River study site and determine bankfull flows at the Big Gypsum site. Determine the rate of channel narrowing through contract work with Dr. Richard of Mesa State.
4. Continue to sample the fish sites on the Yampa and 15-Mile Reach for at least two years (2003 and 2004). The drought of record statewide occurred in 2002. The hydrograph for the Yampa River was severely reduced in 2002 from flows during the sampling period. Median peak flow on the Yampa River was 9880 cfs and median minimum flow was 129 cfs (84 years) at the Maybell gage. In 2002, the peak flow was 3420 cfs and the minimum flow was only 2 cfs. The flows in the 15-Mile Reach in 2002 were also lower. The peak flow was only 2780 cfs and the minimum flow was 58 cfs compared to the median peak of 13500 cfs and the median minimum flow of 558 for the Palisade gage (11 years). Fish population data collected in 2003 could provide data on impacts from the 2002 flows. A result of this continued sampling would be validation of projections about impacts of habitat loss on fish density and biomass.
5. Complete and report on habitat availability for roundtail chub analysis.
6. Perform polygon analysis for the other fish native and nonnative in the 15-Mile Reach and the Yampa River. Include the new two additional years of fishery data for developing meso- habitat suitability. These species include roundtail chub, speckled dace, common carp, white sucker, channel catfish, smallmouth bass, largemouth bass and green sunfish.

ACKNOWLEDGEMENTS

In 1998 and 1999, the hydraulic modeling was contracted with the Department of Earth Resources at Colorado State University. The contract Dr. Ellen Wohl and Greg Stewart administered performed the work for his M.S. project. Greg supervised the habitat quantification portion in the field and performed the hydraulic modeling for Duffy and Corn Lake. I greatly appreciated the enthusiasm and energy Greg put into this study and the long hours he spent setting up the technical equipment and calibrating the SMS model. Greg graduated in the fall of 2000 and is now enrolled at Oregon State University. The 2-D modeling for Clifton, Lily Park, Sevens and Dolores was done in 2002 by contract administered by Craig Addley, Dept. Civil & Environmental Engineering, Utah Water Research Laboratory, at Utah State University. It was a great pleasure to work with Mr. Addley. I learned much about the modeling process from him and his associates. District Wildlife Managers Brad Petch and Chuck Woodward were very helpful and provided valuable assistance and information concerning landowners and logistics on the Yampa River. I am very grateful to Tom Deacons who allowed us access to the river on his property in the Duffy area. Also, I thank the Cross Mountain Ranch and Phil George for allowing access to the Sevens Ranch and Lily Park for habitat surveying and the other property owners who granted access for electrofishing. On the 15-Mile Reach, the main property owner was the BOR and the property managers at the CDOW were Steve Yamashita and Lyle Sidener. Also, Charlie Shannon graciously worked with us for radio-tracking fish on the property. The Clifton Water District (Dave Reinertsen and Dale Tooker) opened access to the Clifton site. Dr. Dan Byers, Cris Sodergren, Jay Bundy and Kevin Bestgen of the Larval Fish Laboratory at CSU did an excellent job with the radio telemetry work in 2000. A copy of their report is available upon request. David Rees of Miller Ecological in Fort Collins performed radio telemetry work in 2001 with DOW seasonal employees. David Rees also made invertebrate collections on the Yampa River. Dave Harper, the DWM in Dove Creek, was helpful setting up the study site on the Dolores River. Dr. David C. Bowden, professor of statistics at CSU, reviewed the methods and the section for population estimates and tests for significance. Lastly, I want to thank all the seasonal and temporary employees for their hard work in doing fieldwork and data entry for this project.

REFERENCES

- Anderson, R. M. 2002. Riverine fish-flow investigations. Colorado Division of Wildlife. Federal Aid Project F-289-R5. Job Prog. Report. Fort Collins, CO 92pp.
- Anderson, R. M. and G. Stewart. 2001. Riverine fish-flow investigations. Colorado Division of Wildlife. Federal Aid Project F-289-R4. Job Prog. Report. Fort Collins, CO 83pp.
- Anderson, R. M. and G. Stewart. 2000. Riverine fish-flow investigations. Colorado Division of Wildlife. Federal Aid Project F-289-R3. Job Prog. Report. Fort Collins, CO 96pp.
- Anderson, R. M. and G. Stewart. 1999. Riverine fish-flow investigations. Colorado Division of Wildlife. Federal Aid Project F-289. Job Prog. Report. Fort Collins, CO 44pp.
- Anderson, R. M. 1998. Riverine fish-flow investigations. Colorado Division of Wildlife. Federal Aid Project F-288. Job Progress Report. Fort Collins, CO 44pp.
- Anderson, R. M. 1997. An evaluation of fish community structure and habitat potential for Colorado squawfish and razorback sucker in the unoccupied reach (Palisade to Rifle) of the Colorado River, 1993-1995. Final Report. Project No. 18. Colorado Division of Wildlife. Federal Aid Project F-288. Job Progress Report. Fort Collins, CO 44pp.
- Andrews, E.D., 1980. Effective and bankfull discharges of streams in the Yampa river basin, Colorado and Wyoming. *Journal of Hydrology* 46, pp. 311-30.
- Bestgen, K. R. 1997. Interacting effects of physical and biological factors on recruitment of age-0 Colorado pikeminnow. Unpublished Ph.D. Dissertations, Colorado State University, Fort Collins, CO. 203 pp.
- Bovee, K. 1996. Perspectives on two-dimensional river habitat models: the PHABSIM experience. *Proceedings - 2nd International Symposium on Habitat Hydraulics*. B150-B152.
- Bovee, K. D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Instream flow information paper 12. FWS/OBS-82/86. United States Department of the Interior, Coop Instream Flow Service Group, Fort Collins Colorado.

- Bundy, J. M. and K.R. Bestgen. 2001. Evaluation of the interagency standardized monitoring program sampling technique in backwater of the Colorado River in the Grand Valley, Colorado. Larval Fish Lab Contribution 119, CSU, Fort Collins, CO.
- Bureau of Reclamation, 1999, draft. Late summer and fall operations report of the HUP managing entities and water managers. BOR, Grand Junction CO, 13 pp.
- Byers, D. W., C. Sodergren, J. M. Bundy, and K. R. Bestgen 2001. Habitat use and movement of bluehead sucker, flannelmouth sucker and roundtail chub in the Colorado River. Larval Fish Laboratory, CSU. Fort Collins Co 32 pp.
- Brunner, G. W. 1998. HEC-RAS River analysis system, user manual version 2.2. U.S. Army Corps of Engineers, Hydrologic Engineering Center. Davis CA pp 230.
- Carlson, C.A., C.G. Prewitt, D. E. Snyder, E. J. Wick, E. L. Ames, and W.D. Fronk. 1979. Fishes and macroinvertebrates of the White and Yampa Rivers, Colorado. Colorado Bureau of Land Management Biological Series 1.
- DeVries, R and S. G. Maurer. 1997. Dolores River Guide. Southwest Natural and Cultural Heritage Asso. Albuquerque, NM.
- Elmbald 2003 (in review). The interagency standardized monitoring program in Colorado result from 1986 to 2000. Final Report, Colorado Division of Wildlife, Grand Junction, CO.
- Espegren, G. D. 1998. Evaluation of the standards and methods used for quantifying instream flows in Colorado. Colo. Water Con. Board. Denver, CO. 18 pp.
- Everhart, W. H. and W. D. Youngs. 1981. Principles of fishery science. Cornell University press.
- Hawkins, J.A., E. J. Wick and D. E. Jennings. 1997. Ichthyofauna of the Little Snake River, Colorado, 1994. Report to: U.S. National Park Service, Denver CO, and Colorado River Endangered Fish Recovery Prog. , Denver CO. 44pp.
- Instream Flow Council. 2002. Instream Flows for Riverine Resource Stewardship. Publisher at www.instreamflowcouncil.org. USA.
- King, I. 1997. The users guide to RMA2 WES Version 4.3. The U.S. Army Corps of Engineers – Waterways experiment laboratory. pp 240.
- Kondolf, G. M., E. W. Larsen and J. G. Williams. 2000. Measuring and modeling the hydraulic environment for assessing instream flows. North American Journal of Fisheries Management 20:1016-1028.

- Leclerc, M., Boudreault, A., Bechara, J.A., and Corfa, G. 1995. "Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology", *Trans. Am. Fisheries Soc.*, **124**(5), 645-662.
- McLean, S.R., S.R. Wolfe, and J.M. Nelson. (1999). Predicting boundry shear stress and sediment transport over bed forms. *Journal of Hydraulic Engineering*. July 1999:725-736.
- McAda, C.W. 2002. Subadult and adult pikeminnow monitoring; summary of results, 1986 – 2000. Recovery Program Project Number 22, Final Report. U.S.F.W.S., Grand Junction, Co. 60pp .
- McAda, C.W, W.R. Elmblad, K.S. Day, M. A. Trammel and T. E. Chart. 1997. Interagency Standardized Monitoring Program; Summary of Results, 1996. Annual report. Recovery Program for the Endangered Fishes of the Upper Colorado River Basin, U.S. Fish and Wildlife Service , Denver, Co.
- Miller, W.H., D.L. Archer, H.M. Tyus and R. M. McNatt. 1982. Yampa River fishes study. Final Report for Memorandum of Understanding 14-16-0006-81-931(IA), U.S. National Park Service. U.S. Fish and Wildlife Service, Salt Lake City, UT.
- Modde, T., W. J. Miller, R M. Anderson, and D. Irving. 1995. Determination of habitat availability and habitat use, and flow needs of endangered fishes in the Yampa River between August and September. Colorado River Recovery Program Report for Project #CAP-9. Denver Colorado. 128 pp.
- Modde, T. and G. Smith. 1999. Flow recommendations for endangereed fishes in the Yampa River. Final Rport submitted to the Recovery Implementation Program for the Recovery of Endangered Fishes in the Upper Colorado River Basin. U.S. Fish and Wildlife Service, Denver, CO. 44 pp.
- Nehring, R. B. 1979. Evaluation of instream flow methods and determination of water quantity needs for stream in the state of Colorado. Colo. Div. Wild. Job Compl. Report. U. S. Fish and Wildl. Service Contract No. 14-16-0006-78-909. 144pp.
- Nelson, J.M. (1996). Predictive techniques for river channel evolution and maintenance. *Air and Soil Pollution*. 90:321-333.
- Nelson, J.M., R.L. Shreve, R. McLean, and T.G. Drake. (1995). Role of near-bed turbulence structure in bed load transport and bed form mechanics. *Water Resources Research*. 31(8):2071-2086.
- Osmundson, D., and L. R. Kaeding. 1991. Recommendations for flows in the 15-Mile Reach during October-June for maintenance and enhancement of endangered fish population in the upper Colorado. Final Report. U. S. Fish and Wildlife Service Grand Junction, CO. 82 pp.

- Osmundson, D., B., P. Nelson, K. Fenton, and D. W. Ryden. 1995. Relationships between flow and rare fish habitat in the '15-mile reach' of the upper Colorado River. U. S. Fish and Wildlife Service Final Report. Grand Junction, CO.
- Osmundson, D., 1999. Longitudinal variation in fish community structure and water temperature in the Upper Colorado River: Implications for Colorado Pikeminnow habitat suitability. Report A, Project No. 48. U. S. Fish and Wildlife Service Final Report. Grand Junction, CO.
- Osmundson, D., 2000. Importance of the 15-Mile Reach to Colorado River populations of endangered Colorado pikeminnow and razorback sucker. Final Report. U. S. Fish and Wildlife Service Position Paper. Grand Junction, CO.
- Osmundson, D., 2001. Flow regimes for restoration and maintenance of sufficient habitat to recover endangered razorback sucker and Colorado pikeminnow in the Upper Colorado River. Project No. 47. U. S. Fish and Wildlife Service. Grand Junction, CO.
- Osmundson, D., 2002. Population dynamics of Colorado pikeminnow in the Upper Colorado River. Project no. 22-A, U. S. Fish and Wildlife Service Final Report. Grand Junction, CO.
- Parasiewicz, P. 2001. MesoHABSIM: A concept for application of instream flow models in river restoration planning. Fisheries. Vol. 26. 9:6-13.
- Pitlick, J., M. M. Van Steeter, B. Barkett, R. Cress and M. A. Franseen. 1999. Geomorphology and Hydrology of the Colorado and Gunnison Rivers and implications for habitats used by endangered fishes. Final Report, U.S. Fish and Wildlife Service, Grand Junction.
- Pitlick, J., and R. Cress. 2000. Longitudinal trends in channel characteristics of the Colorado River and implications for food-web dynamics. Final Report. University of Colorado, Boulder.
- Prewitt, C. G. 1977. Catostomid fishes of the White and Yampa Rivers Colorado. M. S. Thesis, Colorado State Univ., Fort Collins, CO. 122 pp.
- Rose, K. L., and D. R. Hahn. 1989. A summary of historic habitat modeling on the Yampa River using the physical habitat simulation system. U.S. Fish and Wildlife Service, Grand Junction, Colo. 18 pp.
- Stewart, G. 2000. Two-dimensional hydraulic modeling for making instream-flow recommendations. M.S. Thesis. Colorado State University. Fort Collins CO.
- Sublette, J. E., M. D. Hatch and M. Sublette. 1990. The Fishes of New Mexico. University of Nextci Press, Albuquerque NM.

- Thompson, D.M., J.M. Nelson, and E.E. Wohl. (1998). Interactions between pool geometry and hydraulics. *Water Resources Research*. 34(12):3673-3681.
- Topping, D.J., D.M. Rubin, J.M. Nelson, P.J. Kinzel III, I.C. Corson. (2000). Colorado River sediment transport. 2. Systematic bed-elevation and grain-size effects of sand supply limitation. *Water Resources Research*. 36(2):543-570.
- Valdez, R. A., W. J. Masslich and A. Wasowicz. 1992. Dolores River native fish habitat suitability study (UDWR Contract No. 90-2559). BIO/WEST Inc. Logan Utah. 118 pp.
- Valdez, R. A., L. Jonas, and J. Munk. 1999. Nonnative fish control in backwater habitats in the Colorado River. Interim progress report, Project 87b. Colorado Division of Wildlife, Fort Collins. 11p.
- Wick, E. J., T.A. Lytle, and C.M. Haynes. 1981. Colorado squawfish and humpback chub population and habitat monitoring, 1979-1980. Progress Report SE-3-3. Endangered Wildlife Investigations. Colorado Division of Wildlife, Denver, Colorado.
- Wick, E. J., J. A. Hawkins and C. A. Carlson. 1986. Colorado squawfish population and habitat monitoring. 1985. Final Report, SE 3-8. Endangered Wildlife Investigations, Colorado Division of Wildlife, Denver, Colorado.
- Williams, J. E., Johnson, J. E., Hendrickson, D. A., Contreras-Balderas, S., Williams, J. D., Navarro-Mendoza, M., McAllister, D. E., & Deacon, J. E. 1989. Fishes of North America endangered, threatened, or of special concern: 1989, Fisheries (Bethesda) 14(6): 2-20.
- Woodling, J. 1985. Colorado's little fish: A guide to the minnows and other lesser know fishes in the state of Colorado. Colorado Division of Wildlife, Denver, CO.
- Wydowski and Hamil 1991. Evolution of a cooperative recovery program for endangered fishes in the upper Colorado River basin. Pages 123-135 in W.L. Minckley and J.E. Deacon, editors *Battle against extinction: native fish management in the American West*. University of Arizona Press, Tucson.

APPENDIX

Tables and Figures

A-Table 1. Density and biomass estimates for all species in **fish per kilometer** and in **kilograms per kilometer** for each study site.

	no./km	No./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
YAMPA RIVER	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	1147	1115	778	653	1136.7	1004.5	633.1	491.9
Flannemouth Sucker	395	376	296	263	413.4	411.6	361.4	227.7
Bluehead Sucker	274	238	309	120	110.5	93.5	26.0	30.1
Roundtail Chub	73	41	54	29	43.8	26.6	13.6	14.9
White S. + Crosses	200	190	106	138	157.6	159.3	63.5	55.9
Channel Catfish	111	109	22	46	161.5	122.7	41.3	58.1
Carp	77	69	45	33	215.3	168.6	118.5	95.2
Smallmouth Bass	20	29	6	37	10.0	10.0	4.3	5.2
Northern Pike	62	22	3	3	24.5	12.3	4.4	4.9
	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
LONG REACH	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	387	403	316	430	509.6	453.8	340.5	291.9
Flannemouth Sucker	25	15	11	5	34.2	19.3	15.6	6.1
Bluehead Sucker	24	23	16	19	14.0	9.5	10.1	12.1
Roundtail Chub	12	25	5	10	12.0	26.6	5.1	9.6
Colo. Pikeminnow	8	5	4	3	18.8	9.4	6.1	4.7
White S. + Crosses	241	242	203	185	265.8	266.6	231.5	176.0
Channel Catfish	19	29	15	23	34.5	39.1	23.7	27.5
Carp	22	8	4	2	101.6	39.7	21.8	10.6
Smallmouth Bass	40	58	58	215	17.2	26.8	22.4	43.7
Northern Pike	17	16	3	6	11.3	16.8	4.2	1.5
	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
MAPPED REACH	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	435	343	467	716				
Flannemouth Sucker	13	5	9	9				
Bluehead Sucker	21	10	12	3		2.6	4.1	2.1
Roundtail Chub	16	7	7	3		3.1	1.2	0.5
Colo. Pikeminnow	11	5	6	3				
White S. + Crosses	272	230	289	248				
Channel Catfish	6	20	66	25				
Carp	6	1	0	1				
Smallmouth Bass	119	51	112	399				
Northern Pike	33	13	3	15				
	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
YAMPA RIVER			Lily Park	Lily Park			Lily Park	Lily Park
Species			2000	2001			2000	2001
Total Fish			6279	3168			2368.6	1760.3
Flannemouth Sucker			2238	1667			1315.7	801.3
Bluehead Sucker			552	346			194.5	114.0
Roundtail Chub			2	2			3.0	0.1
Colo. Pikeminnow			5	2			0.0	0.0
White S. + Crosses			14	2			1.1	0.6

Channel Catfish			3668	1395			555.4	526.3
Carp			186	171			193.4	203.8
Smallmouth Bass			121	501			69.9	87.0
Northern Pike			19	14			35.5	27.2
	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
COLORADO RIVER		CORN L.	CORN L.	CORN L.		CORN L.	CORN L.	CORN L.
Species		1999	2000	2001		1999	2000	2001
Total Fish		3962	3417	4007		2760.8	2854.1	2605.3
Flannelmouth Sucker		1550	998.75	1661.75		1261.2	1268.9	1280.6
Bluehead Sucker		1573	1182.25	1272		806.4	504.4	596.1
Roundtail Chub		192	357	170.5		57.2	68.0	41.2
Colo. Pikeminnow		5	0	0		9.3	18.8	5.7
White S. + Crosses		139	124	552		56.2	43.2	120.3
Channel Catfish		195	301.25	440.5		180.9	228.4	354.2
Carp		309	525.25	198.5		389.6	722.4	207.0
	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
COLORADO RIVER		CLIFTON	CLIFTON	CLIFTON		CLIFTON	CLIFTON	CLIFTON
Species			2000	2001		1999	2000	2001
Total Density estimate			3766	4547			3207	3341
Flannelmouth Sucker			1822	1563			1280	1075
Bluehead Sucker			1138	1164			452	496
Roundtail Chub			437	357			100	94
Colo. Pikeminnow			2	2				
White S. + Crosses			333	199			116	64
Channel Catfish			641	530			708	447
Carp			570	845			552	1165
	no./km	no./km	no./km	no./km	kg/km	kg/km	kg/km	kg/km
DOLORES RIVER			BIG GYP	BIG GYP			BIG GYP	BIG GYP
Species			2000	2001			2000	2001
Total Density estimate			196.6	231.7			259.0	48.7
Flannelmouth Sucker			35.8	105.9			88.7	1.5
Bluehead Sucker			3.0	12.7			7.0	0.3
Roundtail Chub			81.0	65.1			14.9	4.5
Channel Catfish			68.6	62.2			100.0	22.6
Carp			24.4	6.0			48.3	19.8
Green Sunfish			5.2	1.5				
Black Bullhead			13.7	3.7				

A-Table 2. Density and biomass estimates for all species in **fish per hectare** and **kilograms per hectare** for each study site.

	no/ha	no/ha	no/ha	no/ha	kg/ha	kg/ha	kg/ha	kg/ha
YAMPA RIVER	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS	SEVENS
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	185.2	180.0	125.6	105.4	183.5	162.1	102.2	79.4
Flannemouth Sucker	63.8	60.7	47.8	42.5	66.7	66.4	58.3	36.7
Bluehead Sucker	44.3	38.4	49.8	19.4	17.8	15.1	4.2	4.9
Roundtail Chub	11.8	6.6	8.6	4.7	7.1	4.3	2.2	2.4
White S. + Crosses	32.3	30.7	17.1	22.3	25.4	25.7	10.2	9.0
Channel Catfish	17.9	17.5	3.6	7.4	26.1	19.8	6.7	9.4
Carp	12.5	11.1	7.2	5.3	34.8	27.2	19.1	15.4
Smallmouth Bass	3.2	4.7	1.0	5.9	1.6	1.6	0.7	0.8
Northern Pike	10.0	3.5	0.5	0.4				
	no/ha	no/ha	no/ha	no/ha	kg/ha	kg/ha	kg/ha	kg/ha
LONG REACH	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY	DUFFY
Species	1998	1999	2000	2001	1998	1999	2000	2001
Total Fish	55.3	57.7	45.3	61.4	72.9	64.9	48.7	41.7
Flannemouth Sucker	3.6	2.1	1.6	0.7	4.9	2.8	2.2	0.9
Bluehead Sucker	3.5	3.3	2.3	2.7	2.0	1.4	1.4	1.7
Roundtail Chub	1.7	3.6	0.7	1.4	1.7	3.8	0.7	1.4
Colo. Pikeminnow	1.2	0.7	0.5	0.4	2.7	1.3	0.9	0.7
White S. + Crosses	34.5	34.7	29.1	26.4	38.0	38.1	33.1	25.2
Channel Catfish	2.6	4.1	2.1	3.3	4.9	5.6	3.4	3.9
Carp	3.1	1.2	0.5	0.3	14.5	5.7	3.1	1.5
Smallmouth Bass	5.7	8.3	8.3	30.7	2.5	3.8	3.2	6.3
Northern Pike	2.4	2.3	0.5	0.8	1.6	2.4	0.6	0.2
	no/ha	no/ha	no/ha	no/ha	kg/ha	kg/ha	kg/ha	kg/ha
MAPPED REACH	DUFFY	DUFFY	DUFFY	DUFFY				
Species	1998	1999	2000	2001				
Total Fish	85.9	67.8	92.3	141.4				
Flannemouth Sucker	2.6	1.1	1.8	1.7				
Bluehead Sucker	4.1	1.9	2.3	0.7				
Roundtail Chub	3.1	1.3	1.4	0.7				
Colo. Pikeminnow	2.2	0.9	1.2	0.7				
White S. + Crosses	53.7	45.4	57.0	49.1				
Channel Catfish	1.2	4.0	13.1	5.0				
Carp	1.2	0.2	0.0	0.2				
Smallmouth Bass	23.5	10.0	22.1	78.9				
Northern Pike	6.4	2.7	0.5	2.9				
	no/ha	no/ha	no/ha	no/ha	kg/ha	kg/ha	kg/ha	kg/ha
YAMPA RIVER			Lily Park	Lily Park			Lily Park	Lily Park
Species			2000	2001			2000	2001
Total Fish			1047.6	528.5			395.2	293.7
Flannemouth Sucker			373.3	278.1			219.5	133.7
Bluehead Sucker			92.1	57.7			32.5	19.0
Roundtail Chub			0.3	0.3			0.5	0.0
Colo. Pikeminnow			0.9	0.3			0.0	0.0

	no/ha	no/ha	no/ha	no/ha	kg/ha	kg/ha	kg/ha	kg/ha
White S. + Crosses			2.3	0.3			0.2	0.1
Channel Catfish			611.9	232.7			92.7	87.8
Carp			31.0	28.5			32.3	34.0
Smallmouth Bass			20.2	83.5			11.7	14.5
Northern Pike			3.2	2.3			5.9	4.5
	no/ha	no/ha	no/ha	no/ha	kg/ha	kg/ha	kg/ha	kg/ha
COLORADO RIVER		CORN L.	CORN L.	CORN L.		CORN L.	CORN L.	CORN L.
Species		1999.0	2000.0	2001.0		1999	2000	2001
Total Fish		765.1	659.9	773.8		533.2	551.2	503.1
Flannemouth Sucker		299.4	192.9	320.9		243.6	245.1	247.3
Bluehead Sucker		303.8	228.3	245.7		155.7	97.4	115.1
Roundtail Chub		37.0	68.9	32.9		11.1	13.1	8.0
Colo. Pikeminnow		1.0	0.0	0.0		1.8	3.6	1.1
White S. + Crosses		26.7	23.9	106.6		10.9	8.3	23.2
Channel Catfish		37.7	58.2	85.1		34.9	44.1	68.4
Carp		59.6	101.4	38.3		75.2	139.5	40.0
			no/ha	no/ha			kg/ha	kg/ha
COLORADO RIVER								
Species			2000	2001			2000	2001
Total Density estimate			600	724			511	532
Flannemouth Sucker			290	249			204	171
Bluehead Sucker			181	185			72	79
Roundtail Chub			70	57			16	15
Colo. Pikeminnow			0	0				
White S. + Crosses			53	32			18	10
Channel Catfish			102	84			113	71
Carp			91	135			88	185
			no/ha	no/ha			kg/ha	kg/ha
DOLORES RIVER			BIG GYP	BIG GYP			BIG GYP	BIG GYP
Species			2000	2001			2000	2001
Total Density estimate			116.3	137.1			153.2	28.8
Flannemouth Sucker			21.2	62.6			52.5	0.9
Bluehead Sucker			1.8	7.5			4.2	0.2
Roundtail Chub			47.9	38.5			8.8	2.6
Channel Catfish			40.6	36.8			59.1	13.4
Carp			14.4	3.5			28.6	11.7
Green Sunfish			3.1	0.9				
Black Bullhead			8.1	2.2				

A-Table 3. Corn Lake polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker.

		Bluehead		Flannemouth			
Polygon	AREA	Density	Biomass	Density	Biomass	Depth	Velocity
Lable	hectare	fish/ha	kg/ha	fish/ha	kg/ha	Meters	m/s
CORN LAKE - 800							
lu-800	2.01	113	72	290	299	1.02	0.41
2r-800	0.87	211	114	23	24	0.56	0.85
3u-800	3.21	102	34	158	80	1.24	0.34
4r-800	1.95	370	187	357	303	0.61	0.66
5b-800	0.05	0	0	0	0	0.57	0.15
6r/u-800	2.26	362	158	315	278	0.61	0.83
7b-800	0.27	0	0	0	0	0.60	0.01
9r/u-800	1.24	193	89	383	61	0.90	0.61
10r/u-800	1.91	546	329	545	491	0.67	0.74
12r/u-800	0.86	458	206	782	552	0.80	0.74
13b-800	0.07	0	0	0	0	0.69	0.05
14r/u-800	2.17	316	74	453	369	0.79	0.71
15b-800	0.14	80	26	121	21	0.53	0.03
16u-800	1.56	230	119	329	218	0.38	0.64
CORN LAKE – 1000							
lu-1000	2.02	156	64	414	224	1.09	0.48
2r-1000	0.89	635	258	109	148	0.63	0.94
3u-1000	3.21	148	54	158	98	1.31	0.40
4r-1000	2.01	286	132	406	298	0.67	0.73
5b-1000	0.05	4	1	0	0	0.64	0.14
6r/u-1000	2.32	369	184	423	344	0.67	0.91
7b-1000	0.29	8	27	18	2	0.65	0.01
9r/u-1000	1.26	329	54	266	318	0.96	0.69
10r/u-1000	1.99	363	158	439	345	0.72	0.81
12r/u-1000	0.90	211	89	755	623	0.85	0.84
13b-1000	0.08	0	0	0	0	0.90	0.08
14r/u-1000	2.27	221	101	306	241	0.81	0.79
15b-1000	0.15	0	0	45	8	0.54	0.03
16u-1000	1.65	233	101	226	187	0.41	0.70
CORN LAKE - 1800							
1u-1800	2.15	314	151	403	305	1.25	0.69
2r-1800	1.01	449	231	107	188	0.76	1.17
3u-1800	3.29	57	28	223	147	1.49	0.61
4r-1800	2.41	375	175	293	218	0.78	0.89
5-1800	0.07	0	0	16	13	0.73	0.15
6r/u-1800	2.64	508	265	229	185	0.81	1.14
7b-1800	0.34	0	0	111	6	0.84	0.02
9r/u-1800	1.30	257	158	352	365	1.07	0.91
10r/u-1800	2.29	324	203	282	268	0.84	1.02
12r/u-1800	1.45	800	345	300	185	0.95	1.08
13b-1800	0.11	64	12	75	88	0.91	0.16
14r/u-1800	2.65	178	89	406	315	0.91	1.00
15b-1800	0.76	100	52	40	7	0.49	1.14
16u-1800	1.89	83	64	147	176	0.52	0.88

A-Table 4. Clifton polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker.

		Bluehead		Flannemouth		Mean	Mean
Polygon	AREA	Density	Biomass	Density	Biomass	Depth	Velocity
Lable	hectare	fish/ha	kg/ha	fish/ha	kg/ha	meters	m/s
CLIFTON 800							
3u-800	1.00	133	77	413	502	0.77	0.39
4u-800	0.18	840	200	nd	nd	0.54	0.73
5sc-800	0.15	55	22	127	64	0.14	0.19
6sc-800	0.24	49	20	51	26	0.12	0.27
8r-800	1.10	479	136	343	155	0.51	0.78
12u-800	1.67	154	74	358	251	0.50	0.51
15f-800	1.48	106	30	120	51	0.42	0.79
18u-800	1.27	317	154	516	378	0.76	0.39
21r-800	1.22	105	40	33	22	0.43	0.81
24u-800	1.35	234	106	267	193	0.93	0.37
27f-800	1.71	275	120	273	206	0.75	0.82
30u-800	3.70	47	18	123	86	1.14	0.24
33u-800	1.24	375	149	585	333	0.51	0.63
37u-800	0.77	512	270	535	415	0.42	0.55
38u-800	0.88	185	77	271	163	0.43	0.72
42u-800	2.12	249	122	520	287	0.65	0.56
45u-800	2.07	359	169	337	249	0.73	0.46
CLIFTON 1000							
3u-1000	1.02	60	34	404	370	0.84	0.44
5sl-1000	0.17	117	47	188	94	0.22	0.30
6sc-1000	0.32	199	80	188	94	0.18	0.38
8r-1000	1.15	629	201	359	221	0.57	0.80
12u-1000	1.82	213	94	463	261	0.59	0.52
15f-1000	1.66	335	149	96	52	0.48	0.74
18u-1000	1.30	169	82	886	544	0.85	0.41
21r-1000	1.30	387	218	65	59	0.50	0.80
24u-1000	1.43	73	49	248	343	0.97	0.41
27f-1000	1.73	347	155	203	189	0.81	0.87
30u-1000	3.71	25	8	47	26	1.20	0.28
33u-1000	1.43	86	27	802	551	0.52	0.59
37u-1000	0.87	90	42	328	345	0.50	0.53
38u-1000	0.98	246	104	86	185	0.50	0.72
42u-1000	2.24	246	67	295	151	0.74	0.58
45u-1000	2.15	273	86	140	84	0.81	0.49
49b-1000	0.13	0	0	0	0	0.89	0.05
50b-1000	0.68	0	0	0	0	1.32	0.03

A-Table 5. Lily Park polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker.

		Bluehead		Flannemouth		Mean	Mean
Polygon	Area	Density	Biomass	Density	Biomass	Depth	Velocity
Lable	hectare	fish/ha	kg/ha	fish/ha	kg/ha	meters	(m/s
LILY PARK - 150 CFS							
1-150	0.35	161	66	493	401	0.24	0.26
2-150	1.50	173	66	278	159	0.20	0.24
4-150	1.36	65	25	473	262	0.28	0.28
5-150	0.95	87	34	443	254	0.23	0.37
6-150	2.44	17	6	116	67	0.55	0.19
7-150	0.42	0	0	0	0	0.23	0.43
8-150	0.58	81	28	751	376	0.61	0.23
9-150	1.61	29	10	235	110	0.65	0.17
10-150	0.48	86	23	709	330	0.38	0.46
11-150	0.34	70	20	711	272	0.34	0.26
12-150	0.05	0	0	0	0	0.47	0.12
13-150	0.32	443	148	888	392	0.33	0.32
14-150	0.38	15	4	1022	538	0.72	0.26
15-150	1.02	0	0	0	0	1.17	0.17
16-150	0.28	360	116	764	394	0.44	0.31
17-150	0.66	18	5	112	51	1.08	0.14
18-150	1.14	21	7	84	44	0.93	0.17
19-150	0.56	11	4	95	50	0.70	0.31
LILY PARK - 300 CFS							
1-300	0.38	264	95	218	201	0.37	0.34
2-300	1.67	95	38	239	152	0.31	0.38
4-300	1.47	201	78	329	203	0.32	0.37
5-300	1.12	124	48	228	144	0.24	0.43
6-300	2.51	46	19	396	247	0.57	0.25
7-300	0.45	0	0	0	0	0.17	0.49
8-300	0.62	154	60	721	489	0.50	0.28
9-300	1.63	35	12	154	80	0.55	0.19
10-300	0.54	311	102	835	486	0.36	0.64
11-300	0.36	148	45	485	294	0.50	0.41
12-300	0.06	0	0	0	0	0.57	0.14
13-300	0.41	220	88	498	307	0.43	0.56
14-300	0.43	112	44	685	462	0.77	0.38
15-300	1.18	20	9	441	305	1.15	0.22
16-300	0.32	195	76	920	550	0.50	0.50
17-300	0.75	83	30	495	348	1.09	0.22
18-300	1.24	19	6	418	270	0.97	0.28
19-300	0.65	81	32	821	488	0.74	0.27

A-Table 6. Sevens polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannemouth sucker.

		Bluehead		Flannemouth		Mean	Mean
polygon	Area	Density	Biomass	Density	Biomass	Depth	Velocity
lable	hectare	fish/ha	kg/ha	fish/ha	kg/ha	meters	m/s
SEVESN 80							
1-80	0.50	155	31	199	173	0.32	0.14
2-80	0.52	286	94	38	83	0.21	0.21
3b-80	0.54	48	13	238	182	0.60	0.07
3a-80	1.38	9	2	39	23	0.53	0.07
4-80	0.96	18	7	23	25	0.41	0.10
5a-80	0.42	41	12	268	283	0.62	0.07
5b-80	0.68	0	0	4	4	0.41	0.09
6-80	0.44	39	14	138	137	0.54	0.08
7-80	1.20	22	7	30	33	0.28	0.14
9-80	1.07	0	0	16	14	0.62	0.05
10-80	1.64	32	6	71	61	0.42	0.12
11-80	0.18	0	0	0	0	0.24	0.02
12-80	0.46	0	0	0	0	0.48	0.09
13-80	0.02	0	0	0	0	0.26	0.00
13-80	1.15	0	0	29	46	0.42	0.09
14-80	1.53	0	0	69	50	0.76	0.04
SEVENS 200							
1-200	0.54	170	109	188	169	0.40	0.25
2-200	0.57	183	40	47	11	0.28	0.34
3b-200	0.59	191	72	471	318	0.66	0.15
3a-200	1.49	11	16	80	104	0.60	0.15
4-200	1.02	16	4	53	75	0.48	0.20
5a-200	0.43	255	53	202	97	0.70	0.16
5b-200	0.70	8	2	46	12	0.50	0.18
6-200	0.51	98	35	164	181	0.66	0.17
7-200	1.30	73	13	36	18	0.36	0.25
8-200	0.86	0	0	0	0	0.24	0.23
9-200	1.16	41	27	132	183	0.73	0.10
10-200	1.79	40	16	86	93	0.53	0.20
11-200	0.22	0	0	13	0	0.34	0.00
12-200	0.46	23	7	47	21	0.64	0.15
13a-200	0.02	0	0	0	0	0.26	0.00
13-200	1.21	17	7	51	44	0.56	0.17
14-200	1.57	22	0	78	45	0.89	0.10

A-Table 7. Duffy polygon area, polygon mean depth, polygon mean velocity and polygon density and biomass for bluehead and flannelmouth sucker.

		Bluehead		Flannelmouth		Mean	Mean
polygon	Area	Density	Biomass	Density	Biomass	Depth	Velocity
lable	hectare	fish/ha	kg/ha	fish/ha	kg/ha	meters	m/s
DUFFY 80							
1	1.4	0		0		0.37	0.11
2	0.4	0		4		0.23	0.36
3	2.7	0		2		0.84	0.05
4	1.0	0		0		0.40	0.08
5	0.3	0		7		0.41	0.18
6	0.5	0		5		0.30	0.21
7	1.0	6		4		0.46	0.14
8	1.0	0		4		0.26	0.25
9	1.1	6		6		0.28	0.15
DUFFY 200							
1	1.6	0		0		0.49	0.18
2	0.6	0		0		0.32	0.53
3	2.9	4		0		0.86	0.12
4	1.1	0		0		0.44	0.17
5	0.4	59		0		0.43	0.34
6	0.5	0		0		0.37	0.33
7	1.2	26		1		0.51	0.28
8	1.2	40		1		0.35	0.35
9	1.3	16		1		0.39	0.22

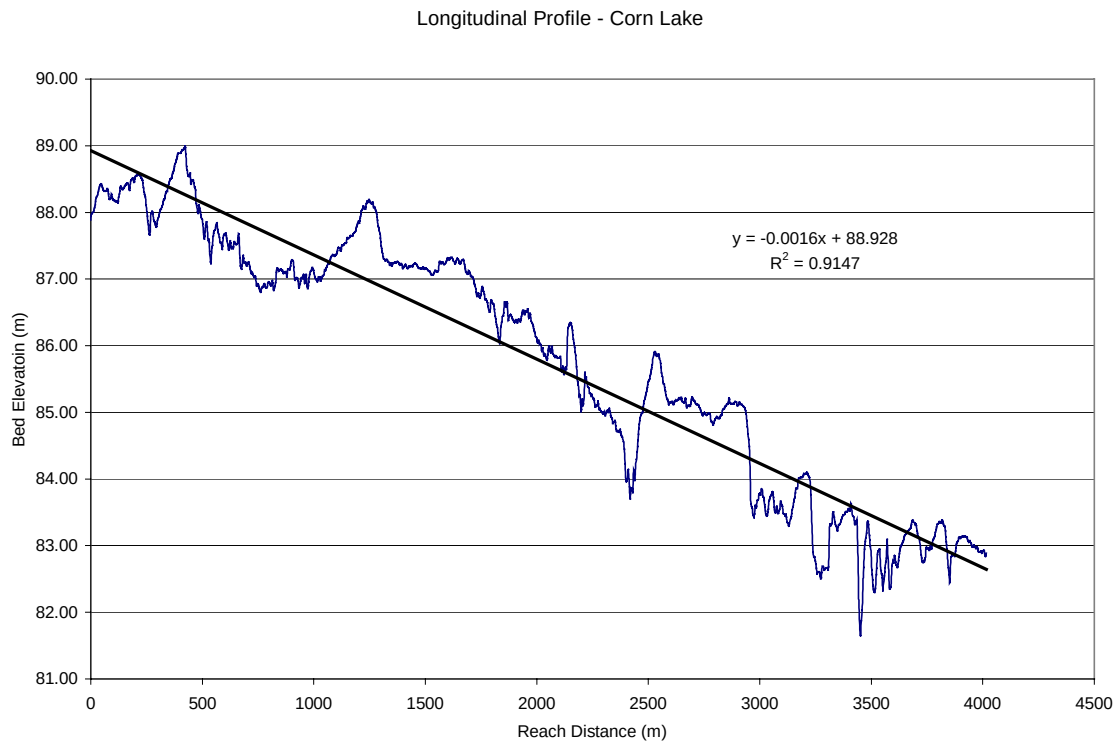


Figure A1. Longitudinal profile for Corn Lake site, Colorado River.

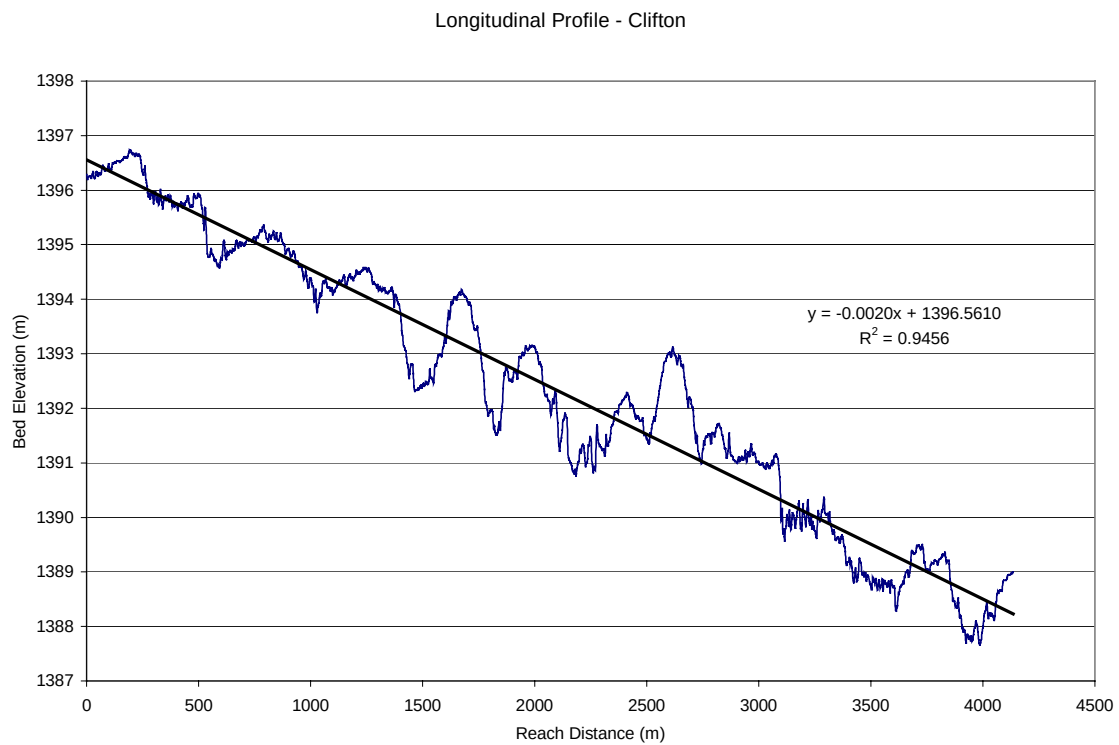


Figure A2. Longitudinal profile for Clifton site, Colorado River.

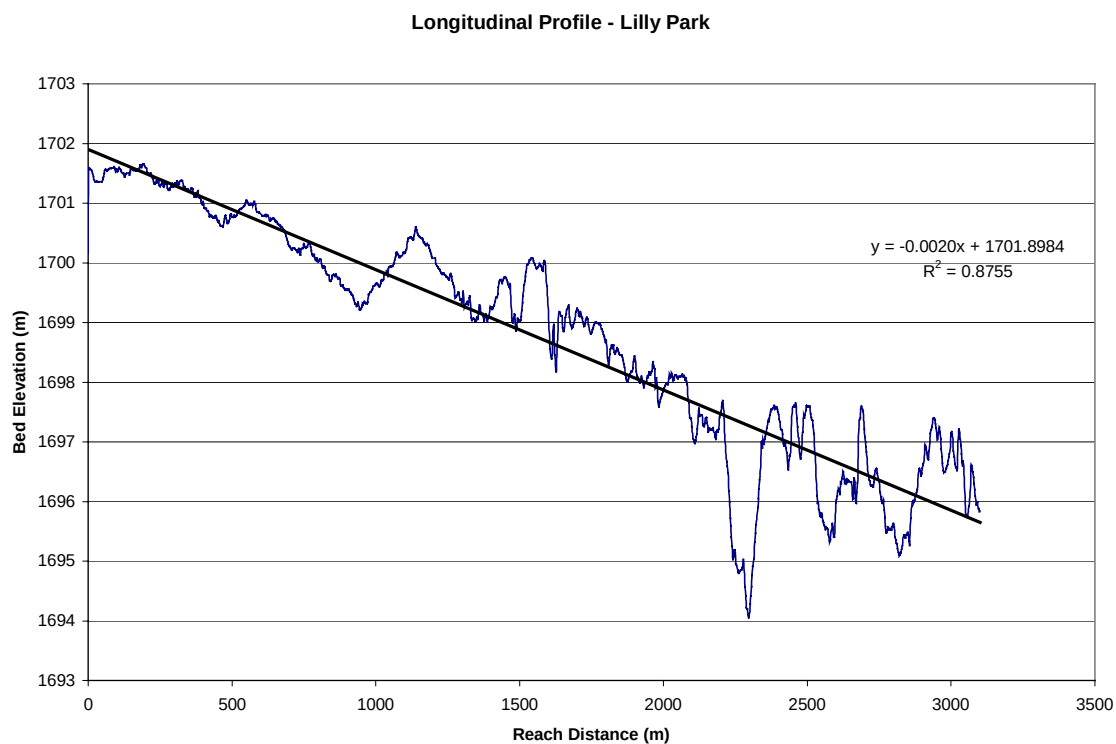


Figure A3. Longitudinal profile for Lily Park site, Yampa River.

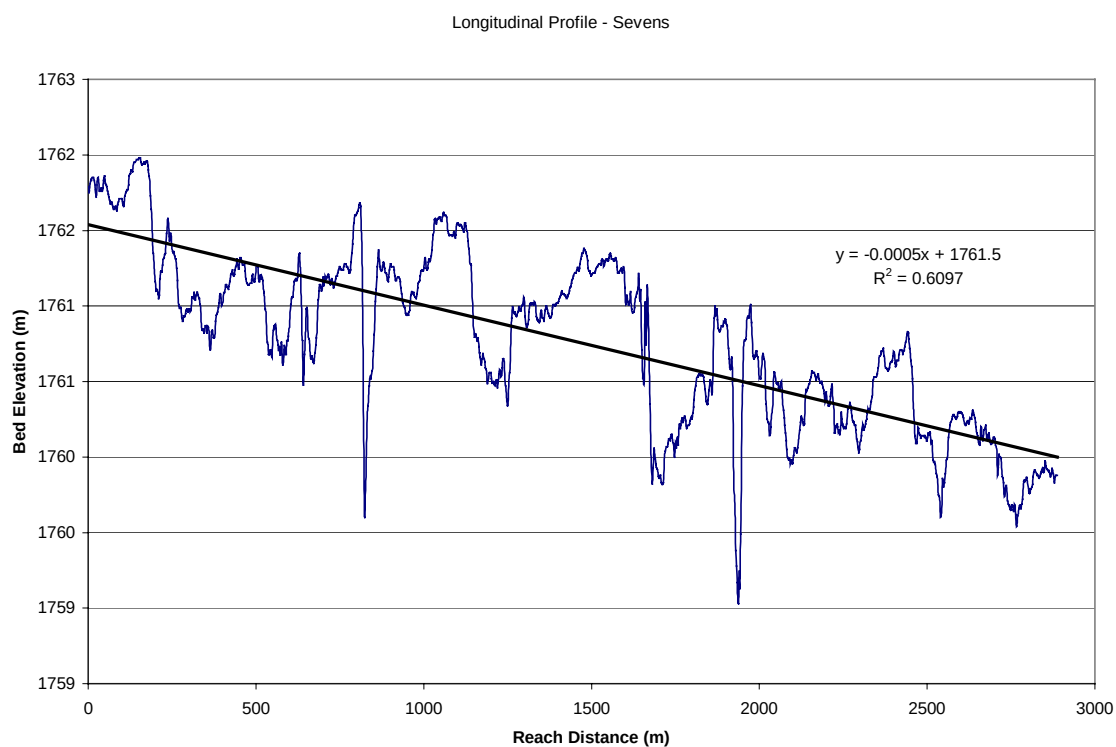


Figure A4. Longitudinal profile for Sevens site, Yampa River.

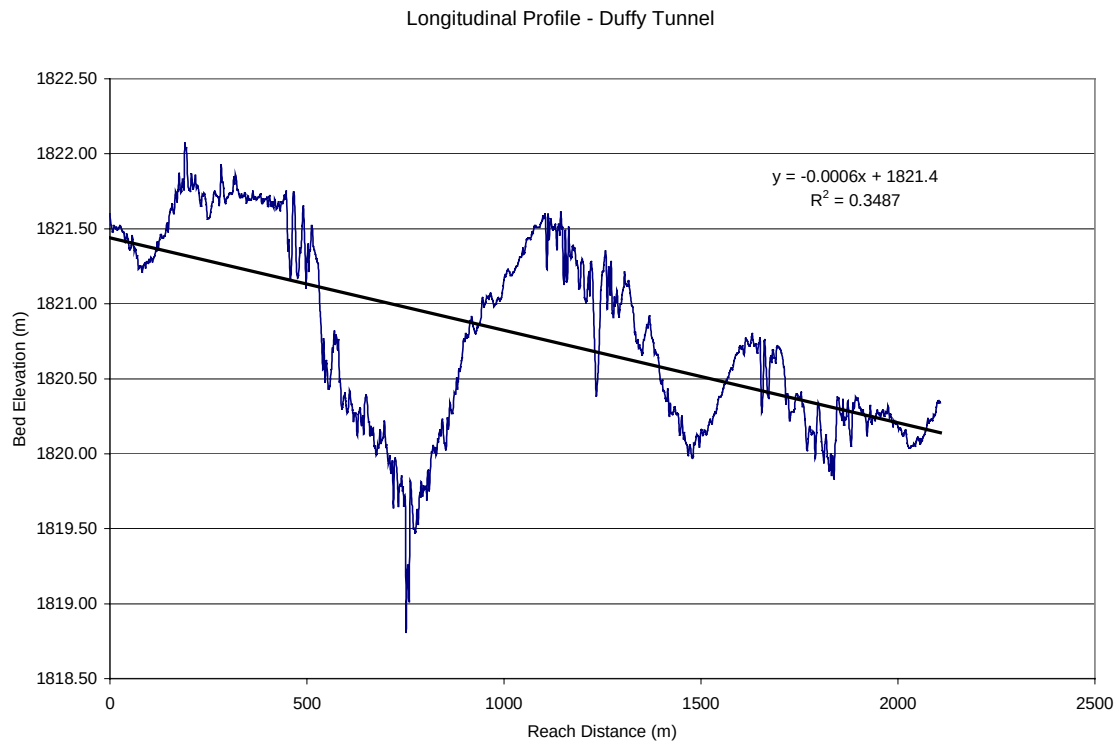


Figure A5. Longitudinal profile for Duffy site, Yampa River.

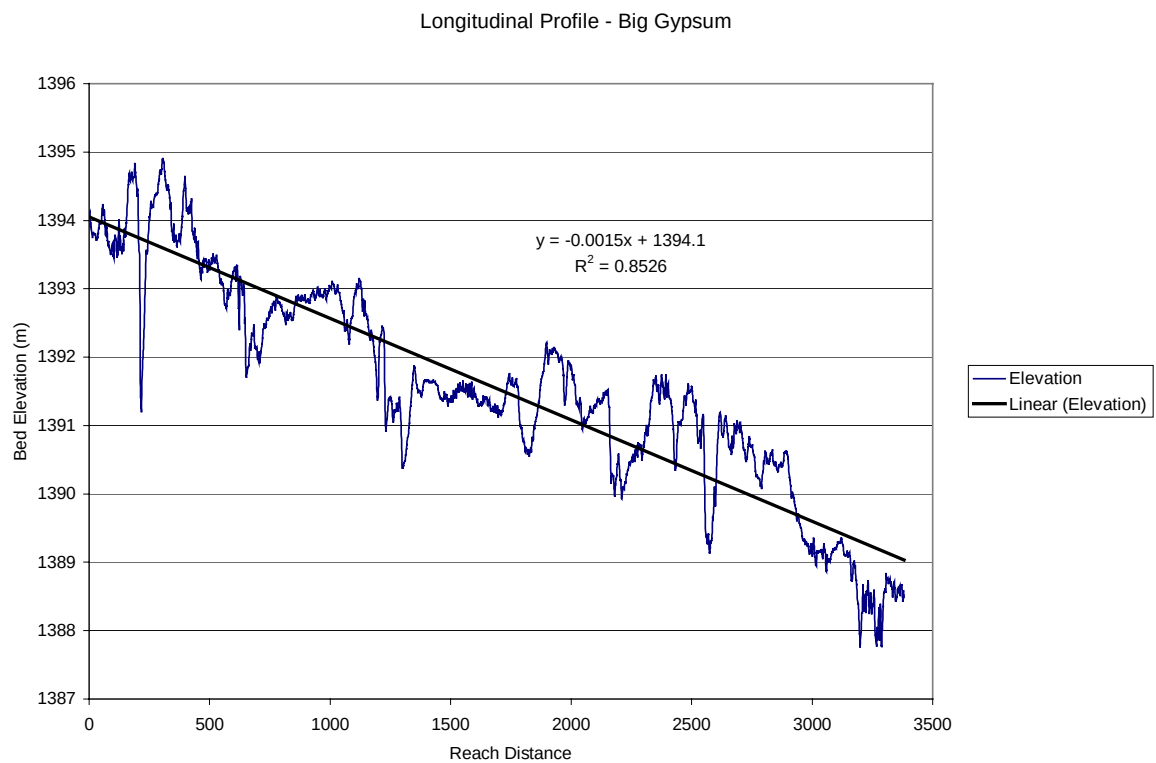


Figure A6. Longitudinal profile for Big Gypsum site, Dolores River.

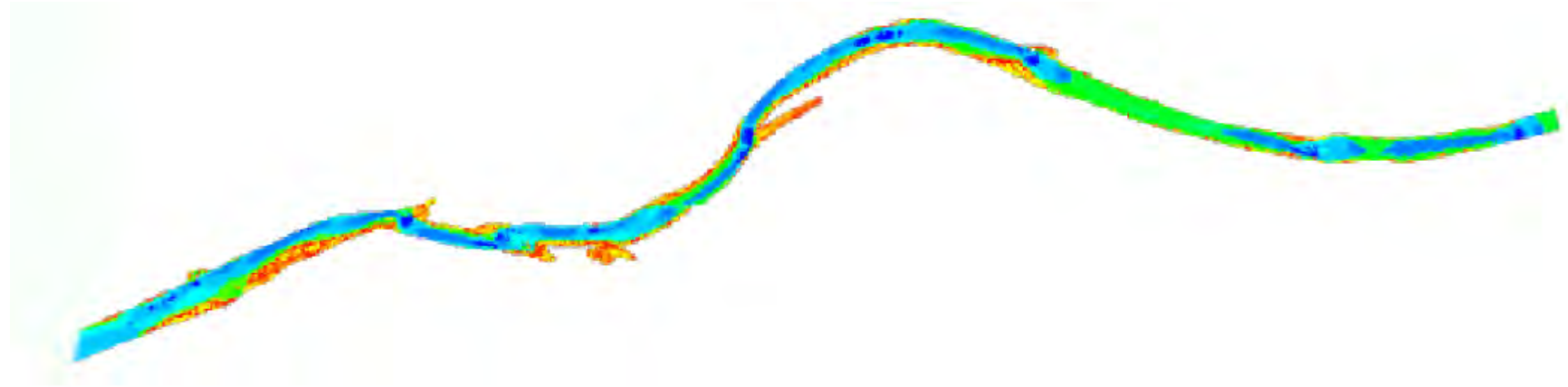


Figure A7. Corn Lake study site with meso-habitat distribution at 1000 cfs, Colorado River.

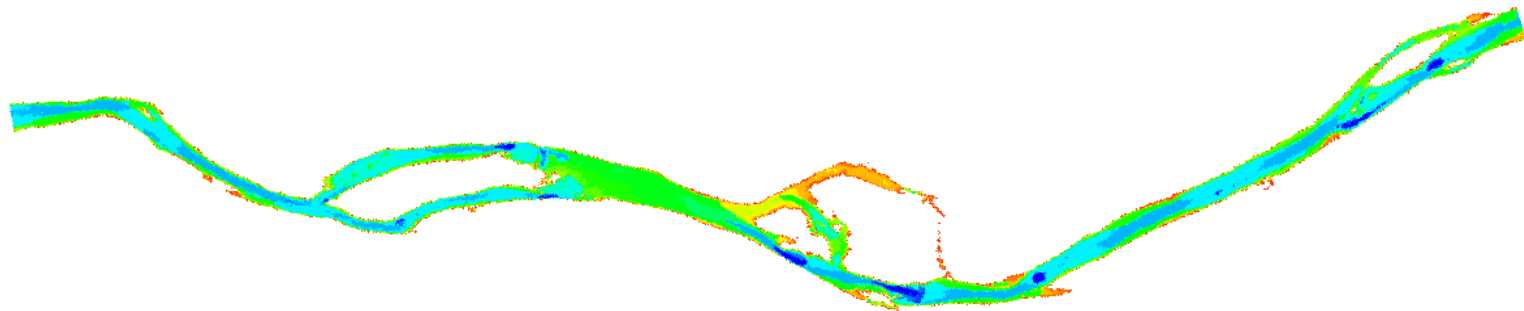


Figure A8. Clifton study site with meso-habitat distribution at 1000 cfs, Colorado River.

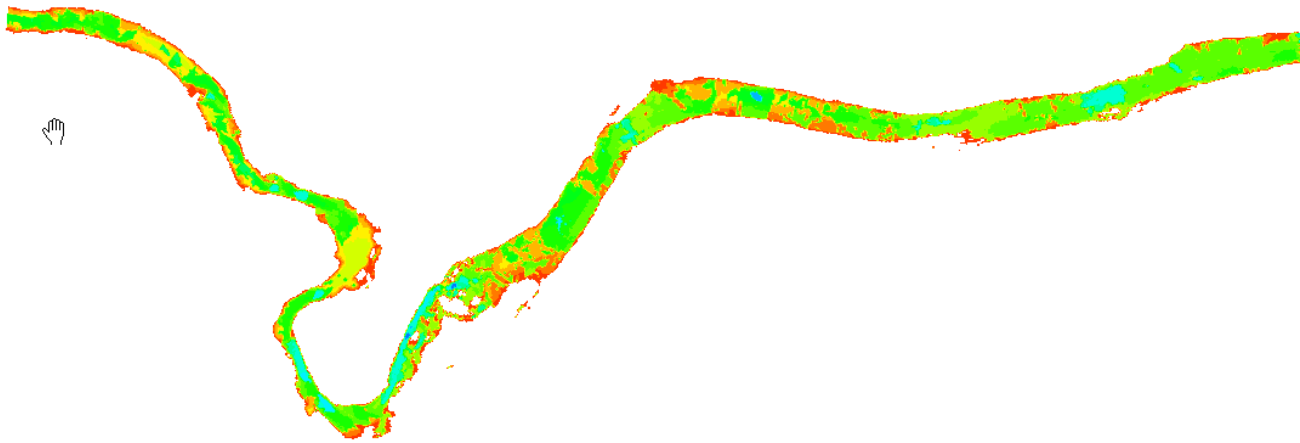


Figure A9. Lily Park study site with meso-habitat distribution at 200 cfs, Yampa River.

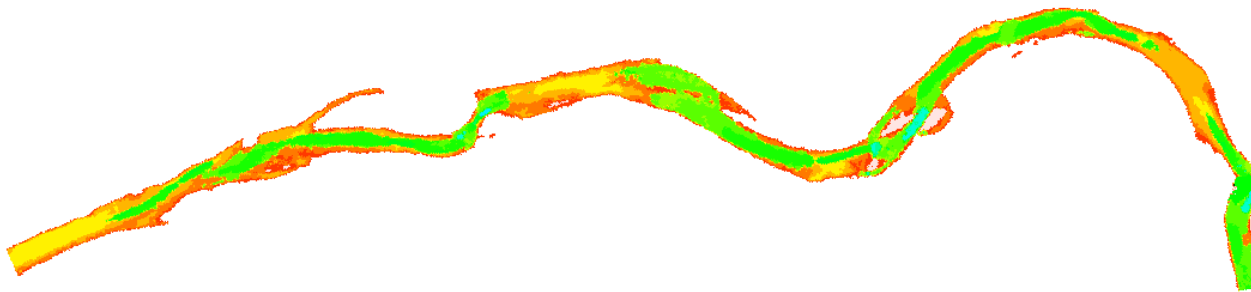
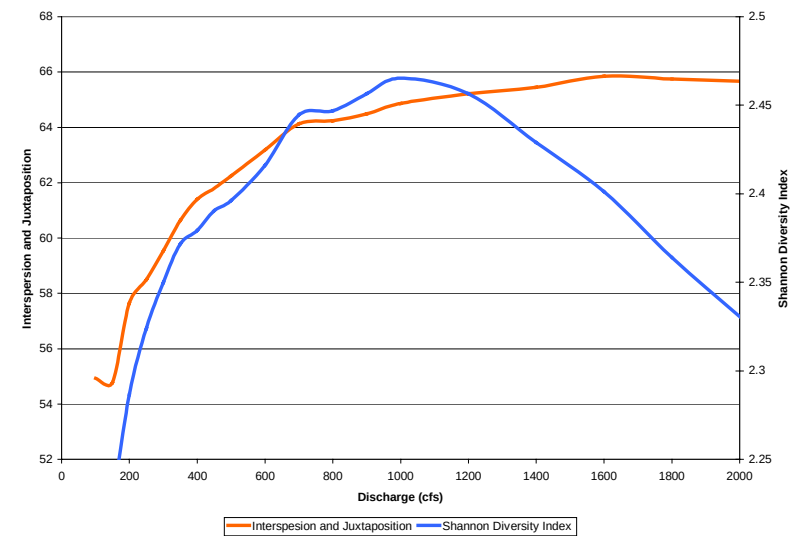
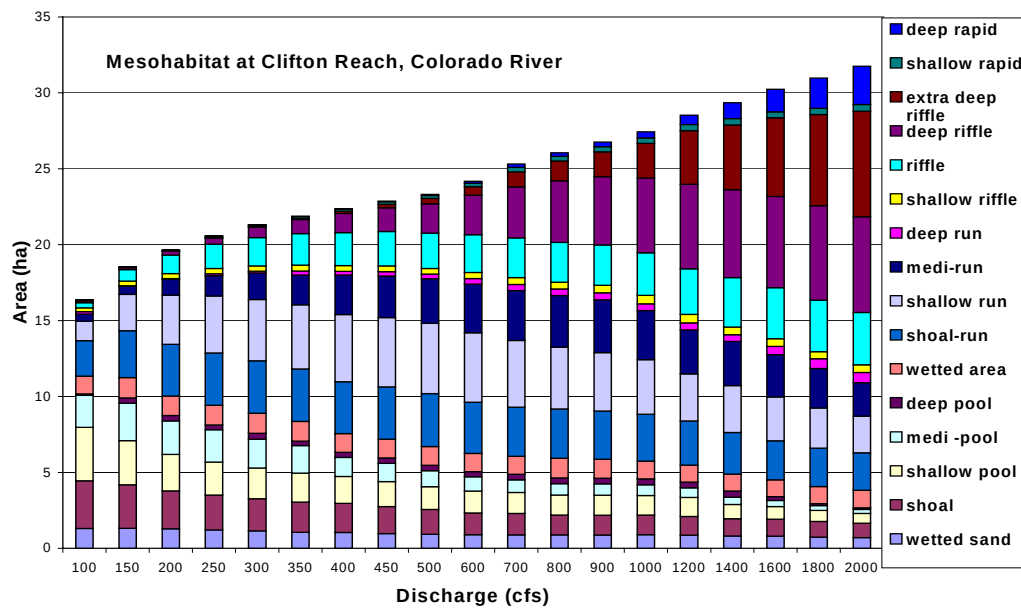
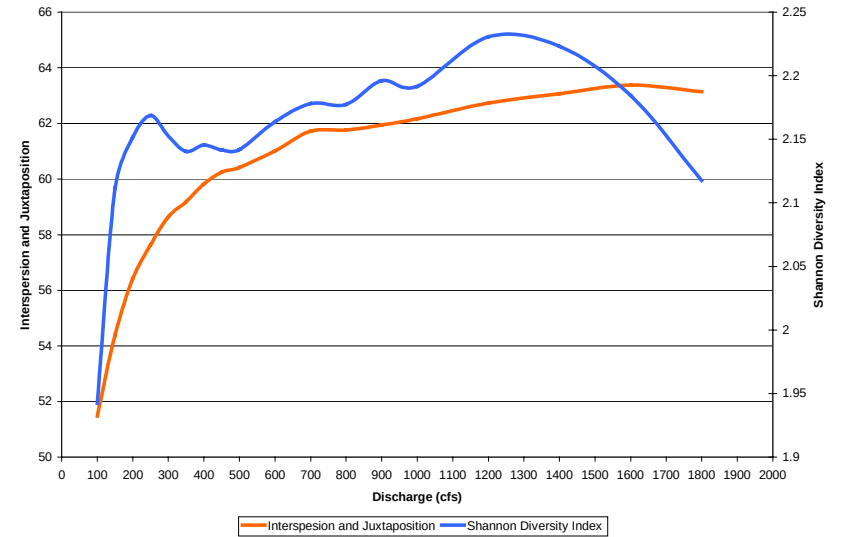
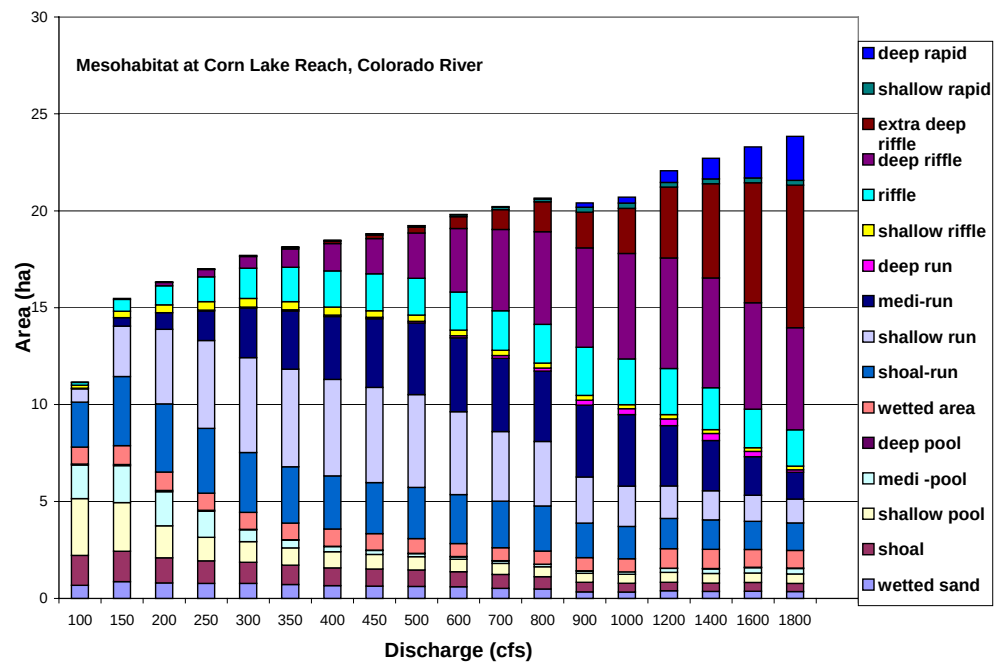
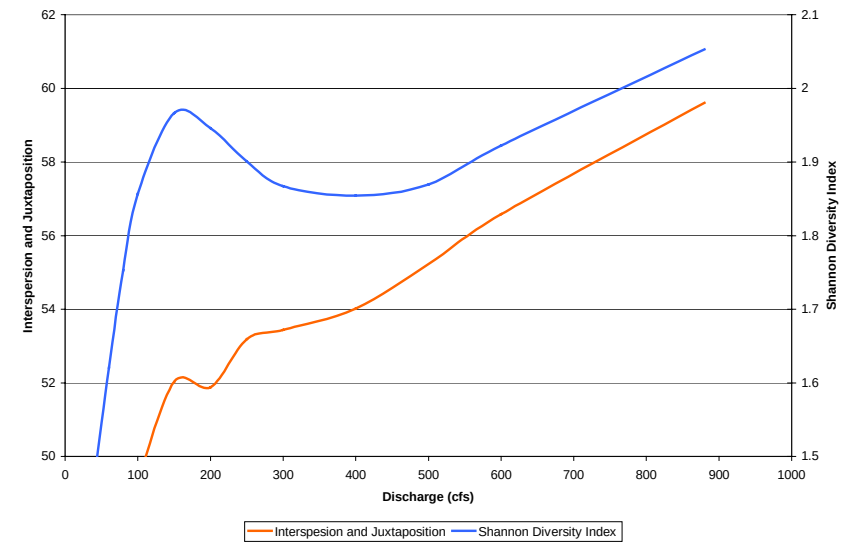
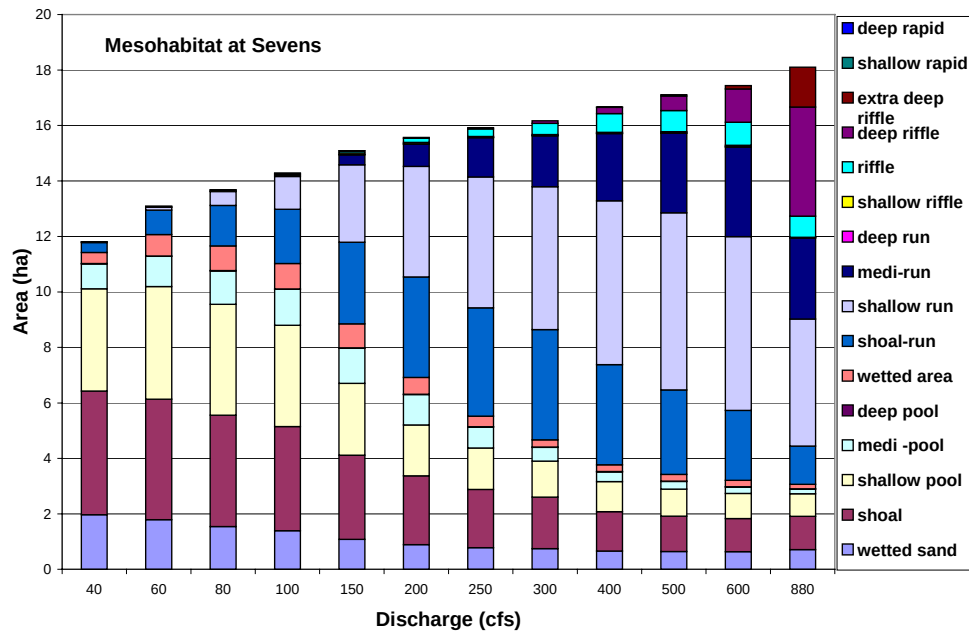
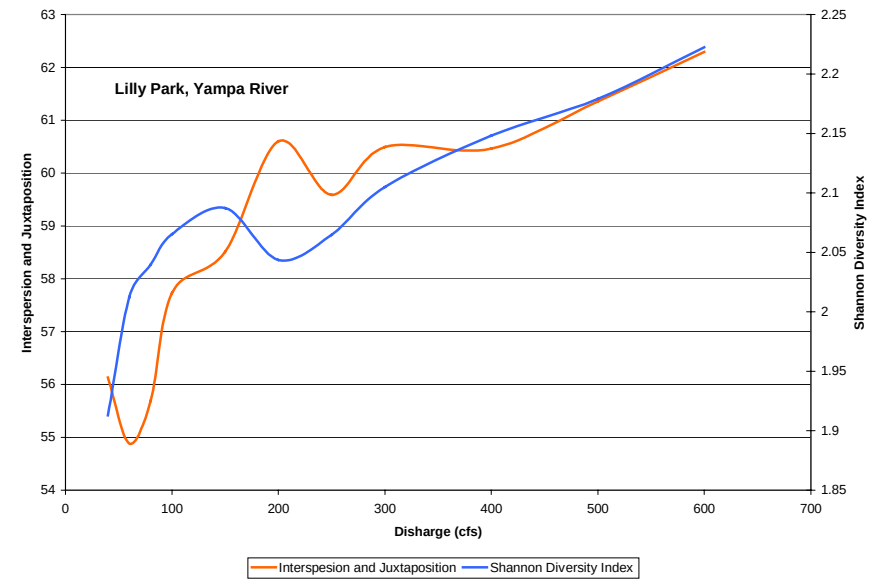
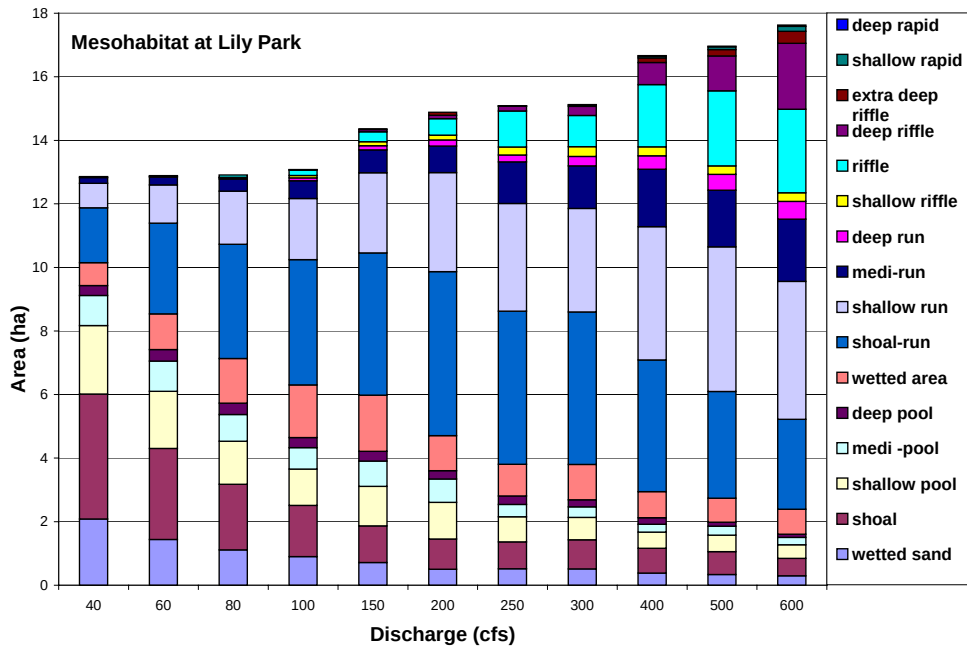


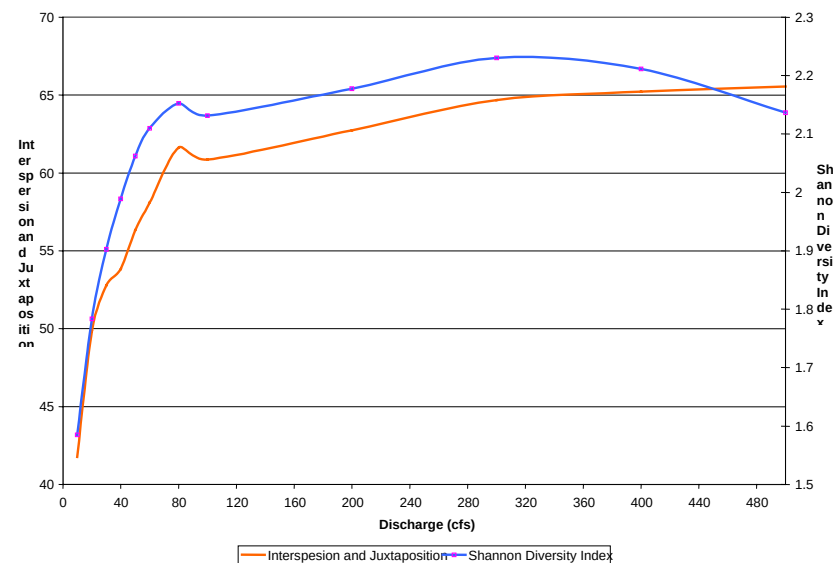
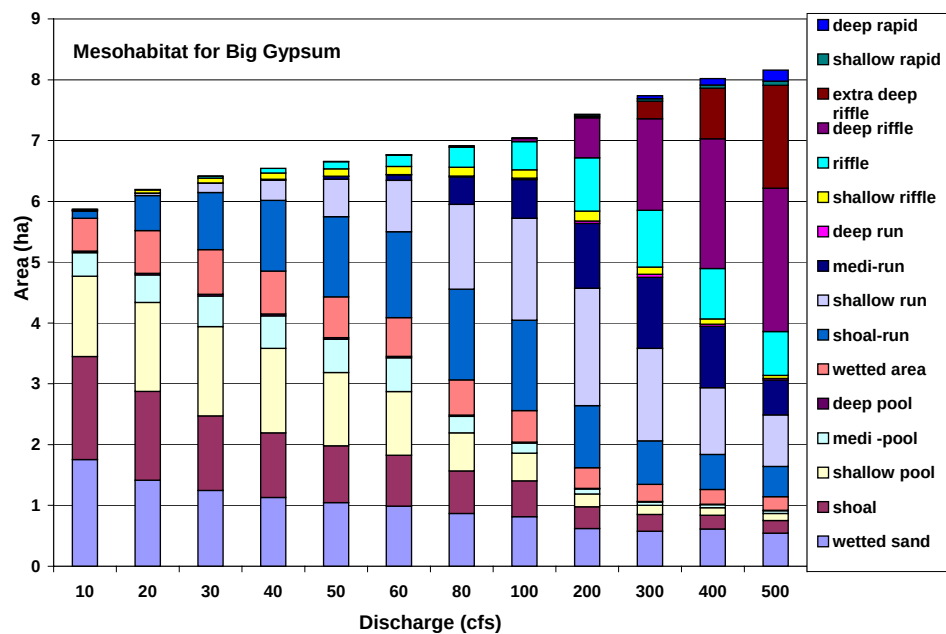
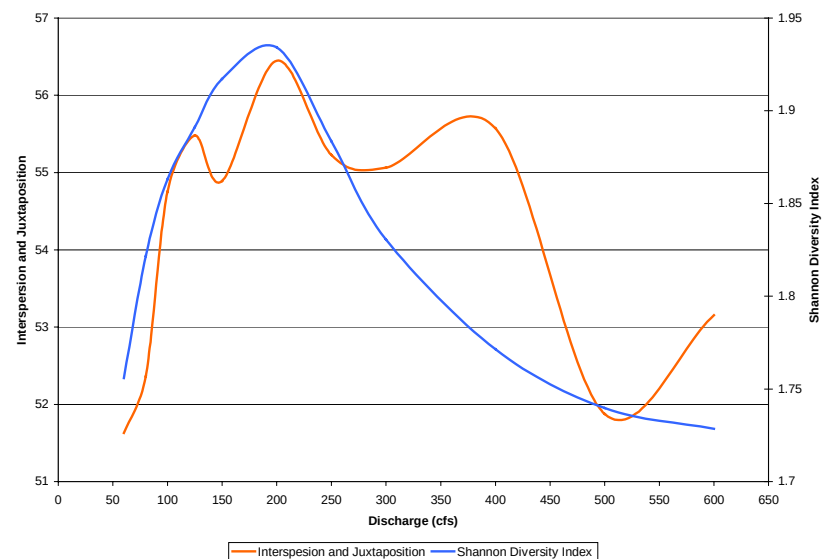
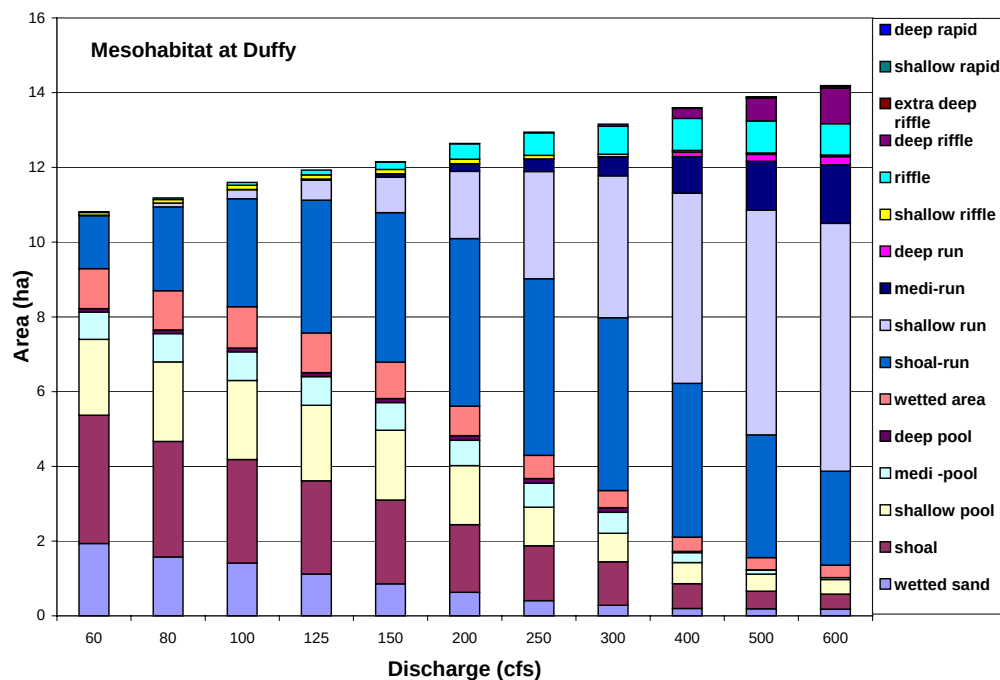
Figure A10. Sevens study site with meso-habitat distribution at 200 cfs, Yampa River.



Figures A11 a, b, c, d. Meso-habitat and Shannon Diversity and Interspersion for modeled flows at Corn Lake (above) and Clifton, Colorado River.



Figures A12 a, b, c, d. Meso-habitat and Shannon Diversity and Interspersion for modeled flows at Lily Park (above) and Sevens, Yampa River.



Figures A13 a, b, c, d. Meso-habitat and Shannon Diversity and Interspersion for modeled flows at Duffy(above), Yampa River and Big Gypsum, Dolores River.

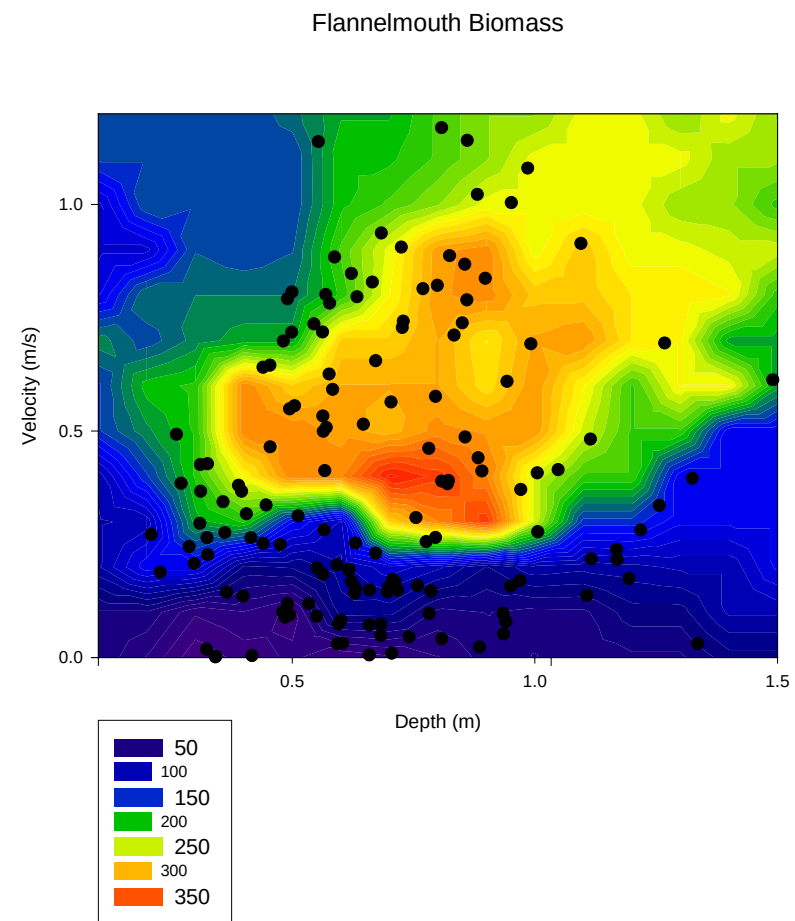
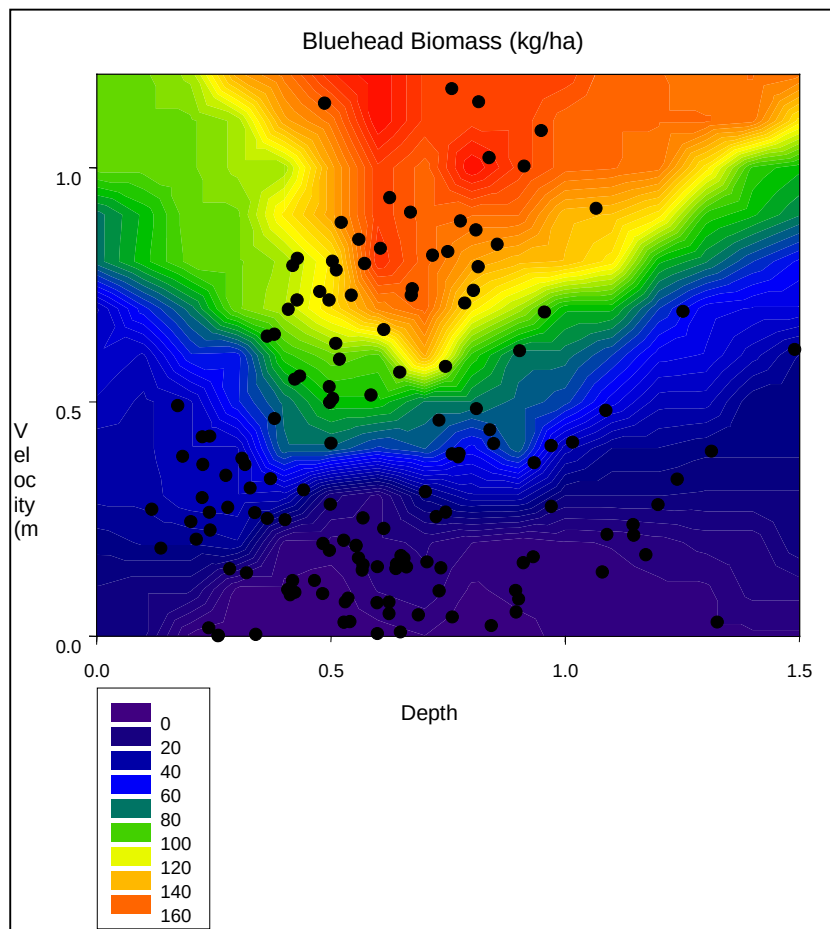


Figure A14. Sigma plot for Bluehead (left) and Flannemouth (right) sucker, showing biomass at polygon mean depth (x axis) and velocity (y axis).

APPENDIX – G

Development of Instream Flow Recommendations In Colorado Using R2CROSS



Colorado Water Conservation Board
Department of Natural Resources
1313 Sherman Street, Room 721
Denver, Colorado 80203

Water Rights Investigations Section

January 1996

The Colorado Water Conservation Board (CWCB)

The CWCB is composed of fourteen members: nine are appointed to represent a major river basin or Denver, and five serve as *ex officio* members (the Executive Director of the Department of Natural Resources, the CWCB Director, the State Engineer, the Division of Wildlife Director, and the Attorney General).

The mission of the CWCB is to promote the protection, conservation, and development of Colorado's water resources in order to secure the greatest utilization of those resources for the benefit of present and future generations, and to minimize the risk of flood damage and related economic losses. The eight goals identified in the CWCB Long Range Plan are listed below.

Goal 1 Protecting Colorado's Interstate Compact Apportionments: To protect Colorado's interstate compact apportionments against any proposed actions which may threaten Colorado's ability to utilize those waters, while pursuing alternatives which resolve or avoid the various water resource problems which may constrain or weaken Colorado's future opportunities.

Goal 2 Development of Colorado's Water Resources: To promote necessary and appropriate development of Colorado's water resources.

Goal 3 Environmental Conflict Resolution: To avoid future environmental conflicts associated with the development and use of Colorado's water resources by preserving the water-dependent natural environment to a reasonable degree in a non-regulatory setting in which water rights and opportunities for future human uses are also protected.

Goal 4 Quality Management: To enhance the leadership, efficiency, and morale within the CWCB staff by 25 percent as measured in annual surveys monitoring productivity and employee satisfaction.

Goal 5 Water Policy Formulation: To strengthen the CWCB's effectiveness as a leader in the identification and analysis of water controversies affecting Colorado, in the evaluation of alternative solutions in cooperation with the affected communities of interest, in the development of consensus support for a preferred resolution to those controversies, and in formalizing official state policy in coordination with the Governor and General Assembly.

Goal 6 Water Information Management Systems: To develop and implement a statewide water information management system by 2003.

Goal 7 Floodplain Management: To minimize Colorado's flood loss vulnerability and related economic impacts.

Goal 8 Public Information: To assure that Colorado citizens, including key communities and interests, have ready access to the high quality information which will be needed for the protection, conservation, and development of Colorado's water resources.

Development of Instream Flow Recommendations In Colorado Using **R2CROSS**

By Gregory D. Espegren
Senior Water Resource Specialist

For additional copies
write or call (303) 866-3441



Colorado Water Conservation Board
Department of Natural Resources
1313 Sherman Street, Room 721
Denver, Colorado 80203

Water Rights Investigations Section

January 1996

Abstract

In 1973, the Colorado State Legislature vested the Colorado Water Conservation Board with the authority to appropriate instream flow water rights in the State of Colorado. Today, the Board holds 1,326 instream flow water rights covering approximately 7,982 miles of Colorado streams. Standardized field and office procedures help to ensure that instream flow recommendations reflect the amount of water required to "preserve the natural environment to a reasonable degree", as prescribed by state statute. R2CROSS is one of the standard techniques employed by state and

federal agencies to model instream hydraulic parameters. R2CROSS was chosen because it is time and labor efficient and produces comparable results to more costly techniques, i.e., the Instream Flow Incremental Methodology. This manuscript provides an overview of Colorado's Instream Flow Program and documentation for the Board's R2CROSS Lotus macro. The R2CROSS macro runs efficiently on an IBM-compatible 80486 personal computer equipped with a hard disk drive, and DOS 6.0, Windows 3.1, and Lotus 1-2-3 Release 4 for Windows software.

Acknowledgments

The Colorado Water Conservation Board would like to thank everyone involved in the development of the Board's R2CROSS Lotus macro. In addition, the author wishes to acknowledge the persons involved in the review and testing of the R2CROSS macro including R. Barry Nehring and Jay Skinner of the Colorado Division of Wildlife, Dr. Eric P. Bergersen, Dr. Kurt Fausch, and Charles Gowan of Colorado State University, Dennis

Murphy of the Bureau of Land Management, Dave Gerhardt of the United States Forest Service, Dan Merriman, Anne Janicki, and Margaret Langdon of the Colorado Water Conservation Board, and Steven O. Sims of the State Attorney General's Office. The Board is very grateful to all of those who participated in the development of the R2CROSS macro and this document.

Disclaimer

The R2CROSS macro is in the public domain, and the recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Colorado State Government-produced program. R2CROSS is provided "as-is" without warranty of any kind, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose. The user assumes all responsibility for the accuracy and suitability of this program for a specific application. In no event will the Colorado Water Conservation Board or the Colorado Division of Wildlife be liable for any damages, including lost profits, lost savings, or other incidental or consequential damages arising from the use of or the inability to use this program.

The CWCB staff verified the calculations performed in its R2CROSS

program with hand-held calculators and by comparison with other Manning's equation-based hydraulic streamflow models. Based upon this verification process, the staff believes that the instream hydraulic parameters summarized in the R2CROSS staging table are accurate calculations of Manning's equation. However, the CWCB does not suggest that the predicted hydraulic parameters will necessarily be realized at any particular stream discharge.

On November 10, 1993, the Colorado Water Conservation Board adopted Rules and Regulations that codified the procedures the Board follows in appropriating instream flow water rights. This document is intended to conform to the procedures presented in the Rules and Regulations.

Table of Contents

Abstract	-ii-
Acknowledgments	-iii-
Disclaimer	-iii-
Table of Contents	-iv-
List of Tables and Figures	-v-
Introduction	-1-
Colorado's Instream Flow Program	-1-
Instream Flow Legislation	-1-
Field Procedures	-2-
Field Data Site Selection	-2-
Hydraulic Data Collection	-3-
Biologic Data Collection	-5-
The Field Form	-5-
Office Procedures	-10-
Background on the R2CROSS Methodology	10-
Biologic Instream Flow Recommendations	-18-
Water Availability Requirements	-19-
Appropriating and Protecting an Instream Flow Water Right	-20-
Summary	-20-
R2CROSS Program Documentation	-21-
Setup and Installation	-21-
Copying R2CROSS to a Hard Disk Drive	-21-
Loading Lotus 1-2-3 and Retrieving the R2CROSS Macro	-22-
Iron Creek Example	-23-
The R2CROSS Menu	-24-
Input	-24-
Verify	-25-
Save	-25-
Calculate	-26-
Graph	-26-
Retrieve	-26-
Printers	-27-
Quit	-27-
Terminating and Reactivating the R2CROSS Macro	-27-

Literature Cited	-28-
Appendix A - Program Calculations	-30-

List of Tables and Figures

Tables

Table 1.	Field equipment list for making streamflow measurements	-4-
Table 2.	Criteria used to determine minimum flow requirements using the R2CROSS single transect method (Nehring 1979)	-19-
Table 3.	Data entry and data editing using the <ENTER> key and arrow keys	-22-
Table 4.	Hydraulic Formulas used in R2CROSS staging table	-34-

Figures

Figure A.	Typical stream cross section	-5-
Figure B.	Field data input sheet (Front Page)	-8-
Figure C.	Field data input sheet (Back Page)	-9-
Figure D.	The R2CROSS Menu	-11-
Figure E.	R2CROSS proof sheet	-12-
Figure F.	Final output from R2CROSS (Page 1)	-13-
Figure G.	Final output from R2CROSS (Page 2)	-14-
Figure H.	Final output from R2CROSS (Page 3)	-15-
Figure I.	Final output from R2CROSS (Page 4)	-16-
Figure J.	Final output from R2CROSS (Page 5)	-17-
Figure K.	Cross section plot from R2CROSS	-18-
Figure L.	Sequence of operations performed by R2CROSS macro	-32-
Figure M.	Lotus 1-2-3 worksheet layout for R2CROSS macro	-33-

Introduction

Colorado's Instream Flow Program originated in 1973 with the passage of Senate Bill 97 (SB 97). Under SB 97, the Colorado Water Conservation Board (CWCB) was vested with the authority to appropriate instream flow water rights in the State of Colorado (§ 37-92-102(3), C.R.S. (1990)). Instream flow water rights are held by the CWCB on behalf of the people of the State of Colorado to "preserve the natural environment to a reasonable degree." Today, the CWCB holds 1,326 instream flow water rights covering approximately 7,982 miles of Colorado streams.

Determining the quantity of water required to preserve the natural environment to a reasonable degree can be a difficult task. The CWCB, in cooperation with the Colorado Division of Wildlife (DOW), has developed standard field and office procedures to ensure that each instream flow appropriation is necessary and reasonable and that the amount of water recommended is available for appropriation.

The R2CROSS methodology described in this document is a valuable tool in developing these instream flow

recommendations. The CWCB uses R2CROSS because it is time and labor efficient and produces results which are comparable to more data intensive techniques (Nehring 1979).

This manuscript is divided into two sections. The first section describes Colorado's Instream Flow Program, including some of the statutory guidelines that have shaped the program. It also describes the standard field techniques and office procedures that are used by the CWCB staff in the development of R2CROSS-based instream flow recommendations. This section is intended to provide an understanding of the procedural and technical aspects of Colorado's Instream Flow Program.

The second section of the manuscript is a users' manual for the CWCB's R2CROSS macro. The CWCB has received many requests for its R2CROSS macro from both the public and private sectors but has been hesitant to release the program without proper documentation. The second section of the manuscript is intended to provide that documentation.

Colorado's Instream Flow Program

Instream Flow Legislation

The CWCB was created in 1937 to serve as the State's chief water planning agency (§ 37-60-101 through 123, C.R.S. (1990)). Today, the CWCB is responsible for the administration of the State's Instream Flow Program, protection of endangered aquatic species, identification of flood plains, funding of new water development and water

conservation projects, and negotiation of inter- and intra-state water planning issues.

The CWCB is a fourteen-member board. The board consists of one Governor-appointee from each of the eight major river drainages in the State and one from the City and County of Denver. Each Governor-appointee must also be confirmed by the Colorado State Senate. Ex-officio members of the board include the

Executive Director of the Department of Natural Resources, the Directors of the CWCB and DOW, the State Attorney General, and the State Engineer. The diverse backgrounds of its board members provides the CWCB with an excellent representation of Colorado's various water interests.

Colorado's Instream Flow Program was created in 1973 when the Colorado State Legislature recognized "the need to correlate the activities of mankind with some reasonable preservation of the natural environment" through the passage of SB 97. Within SB 97, the definition of beneficial use was changed to include minimum stream flows and the CWCB was vested with the authority to appropriate "waters of natural streams and lakes ... as may be required ... to preserve the natural environment to a reasonable degree." SB 97 was amended by Senate Bill 414 in 1981, Senate Bill 91 in 1986, Senate Bill 212 in 1987, and Senate Bill 54 in 1994. These changes and amendments are consolidated within § 37-92-102(3), C.R.S. (1990), the Instream Flow statute.

The Instream Flow statute sets forth the guidelines for the administration of Colorado's Instream Flow Program. The statute vests the CWCB with the exclusive authority to appropriate and acquire instream flow and natural lake level water rights. In order to encourage other entities to participate in Colorado's Instream Flow Program, the statute directs the CWCB to request instream flow recommendations from other state and federal agencies prior to initiating an instream flow appropriation. The CWCB routinely requests instream flow recommendations from the DOW, Colorado Division of Parks and Outdoor Recreation, United States Department of Agriculture, and United States Department of Interior (the "cooperating agencies").

Prior to appropriating an instream flow water right, the statute requires the CWCB to:

- (1) "determine that the natural environment will be preserved to a reasonable degree by the water available for the appropriation to be made;
- (2) determine that there is a natural environment that can be preserved to a reasonable degree with the CWCB's water right, if granted;
- and (3) determine that such environment can exist without material injury to water rights" (§ 37-92-102(3c), C.R.S. (1990)).

The CWCB makes these determinations based upon a review of the supporting technical data and a final instream flow recommendation prepared by the CWCB staff.

Standardized field and office procedures have been developed to help ensure that final instream flow recommendations meet statutory guidelines and are consistent. The standard field procedures that were established concern selection of transect sites and collection of hydraulic and biologic data. Standard office procedures have been established for determining biological instream flow recommendations using output from R2CROSS and for analyzing water availability.

Field Procedures

Instream flow recommendations are typically based on hydraulic and biologic data collected during a single field visit. Hydraulic data collection consists of setting up a transect, surveying stream channel geometry, and measuring stream discharge. Biologic data is gathered to document the existence of a natural environment. The biologic data usually consists of a fish sample, collected by electrofishing, and an aquatic invertebrate sample.

Field Data Site Selection

The R2CROSS method requires that stream discharge and channel profile data be collected in a riffle stream habitat-type. A riffle is a stream segment that is controlled by channel geometry rather than a downstream

flow control. Riffles are most easily visualized as the stream reaches which would dry up most quickly should streamflow cease.

Biologically, riffles are essential to the production of benthic invertebrates and the passage, spawning, egg incubation, feeding, and protective cover of fish. Riffles are also the stream habitat-type most sensitive to changes in hydraulic parameters with variation in discharge (Nehring 1979). Riffles are critical to a healthy aquatic environment because small reductions in streamflow may result in large reductions in water depth and the amount of wetted perimeter available for aquatic habitat. Maintaining adequate streamflow in riffles also preserves the natural environment in other important stream habitat-types such as pools and runs (Nehring 1979).

Hydraulic engineers have developed several mathematical models and equations to predict instream hydraulic parameters (Chow 1959). Manning's equation is one such model that is well-suited to the riffle stream habitat-type (Grant et al. 1992). In order to maximize the reliability of Manning's equation, transects are placed within a riffle so that streamflow is uniform across the transect (Grant et al. 1992). The transect represents the average stream width, depth, and cross-sectional area within the riffle being characterized. Transects should be located in areas that exhibit natural banks or grasslines and concentrated water flow, free from braiding. They should not be located on eroded or undercut streambanks.

Hydraulic Data Collection

Stream discharge is measured using standardized procedures established by the United States Geological Survey (USGS) (Buchanan and Somers 1969). On streams less than 50 feet in width, channel geometry is typically measured using sag-tape methodology (Silvey 1976; Ray and Megahan 1979). Larger

streams typically require the use of a land survey level and stadia rod (Benson and Dalrymple 1967). A list of required field equipment for making streamflow measurements is provided in Table 1.

The sag-tape methodology consists of suspending a steel tape from bank to bank across the stream channel, perpendicular to the streamflow (Figure A). Metal cross section stakes are driven into the ground above the grassline. The steel tape is suspended by attaching the zero-end of the tape to one of the metal stakes, stretching the tape across the stream, and then attaching the other end to a tape clamp and spring scale fastened to the metal stake on the opposite streambank. A minimum of 15 pounds of tension is applied to the tape, as the tape is drawn up and clamped. A survey level and stadia rod are used to adjust the ends of the tape up or down until they are level, thereby producing a consistent datum from which vertical distance measurements can be read.

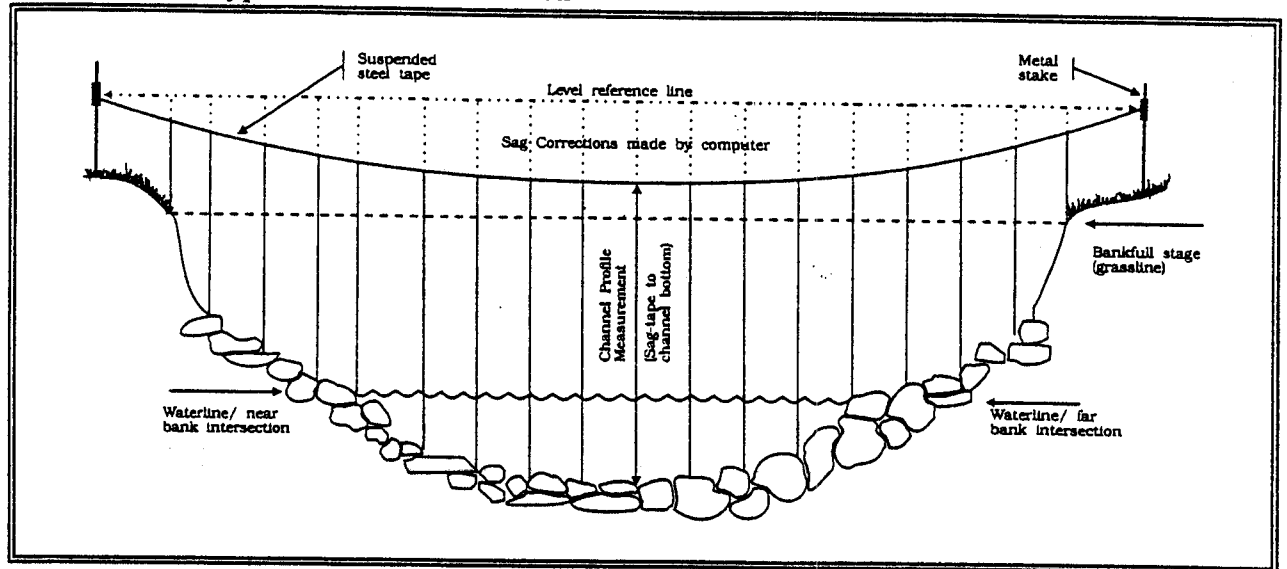
The R2CROSS program uses the standard weight of a one-foot section of the steel tape, tape tension, and the length of tape in suspension to correct horizontal distance and vertical depth measurements made from the sagging tape. The program adjusts the coordinates at each cross section vertical so that the corrected measurements correspond to a level datum from stake to stake and not the curved datum created by the sagging tape (Figure A).

On larger streams, vertical measurements between the suspended tape and the stream channel may be replaced with readings using a survey level and stadia rod. The suspended tape is then used to measure only the horizontal location of each cell vertical. There is no need to precisely level the ends of the suspended tape or to record the tape tension as no sag corrections are required.

Table 1. Field equipment list for making streamflow measurements

Equipment	Description
100' Steel Survey tape	Stretched between cross section stakes. (Obtain standard weight of a 1.0 foot section of tape from manufacturer)
Spring Tension Scale	Used to measure pounds of tension on steel tape when stretched between stakes.
Tape Clamp Handle	Holds tape in tension.
Cross Section Stakes	Two 24"-36" metal stakes used to maintain tape tension and to level steel tape. Must be strong enough to be driven into rocky stream bank.
Discharge Wading Rod (or Stadia Rod)	Used to measure vertical depths from suspended tape to stream channel.
Level, Tripod, and Stadia Rod	Used to level ends of suspended tape and to measure slope.
Current Meter	Pygmy, Price AA, Marsh-McBirney or similar devise used to measure stream velocity.
Hand Sledge Hammer	Used to drive cross section stakes into streambank.
Staging Pin	Used to detect changes in discharge during the streamflow measurement.
100' Fiberglass Tape	Used to measure horizontal distance from suspended tape to water-slope stadia rod readings.
Field Forms and Clipboard	Standardized form to ensure complete set of field data.
Miscellaneous Items	Camera, film, maps, waders, stopwatch and calculator.

Figure A. Typical stream cross section



Biologic Data Collection

Biologic sampling is conducted to document the existence of a natural environment. Coldwater fish species, particularly salmonids, have been used to indicate the existence of such a natural environment in the majority of the CWCB's instream flow appropriations to date. Warmwater fish species and other aquatic life forms may be used to document the existence of a natural environment in more downstream, low-elevation stream segments. In addition to salmonids, the CWCB has used amphibians, such as frogs and salamanders, and warmwater fish species, including the endangered fishes of the Colorado River basin, as the biologic basis for instream flow appropriations.

Biologic data typically consists of a fish sample, collected by electrofishing, and an aquatic invertebrate sample. Captured fish are identified and measured and a length-frequency distribution is constructed for each species. The sample is not tied directly to the R2CROSS hydraulic modeling but it may be used to refine the biologic instream flow recommendation to

meet the specific habitat requirements of unique populations.

The Field Form

The CWCB and DOW use a standardized field form to record all field data. The use of this form helps to ensure that all instream flow recommendations are based upon a uniform set of field data. The front page of the form provides space for cross section "Location Information", "Supplemental Data", "Channel Profile Data", an "Aquatic Sampling Summary", and "Comments" (Figure B). The back page is dedicated to "Discharge/Cross Section Notes" (Figure C).

The "Location Information" section of the field form is used to describe the location of the cross section as well as the date and names of the members of the field crew. Geographic information can be obtained from either USGS or United States Forest Service (USFS) maps. Water divisions and DOW water codes can be obtained from the State Engineers' Office, the CWCB, or the DOW.

The "Supplemental Data" section is used to provide supporting documentation of the field data collection effort. Most importantly, this section is used to record the tape manufacturer's standard weight (lbs/ft) and tape tension (lbs). The R2CROSS program uses this information, together with the length of tape in suspension, to adjust vertical distances measured from the sagging tape to a level reference datum.

The "Channel Profile Data" section of the form is used to establish the relationship between the sag-tape cross section and the stream. Stadia rod readings are taken at each end of the suspended tape and at the water surface on the right and left streambanks. These readings are recorded within the "Rod Reading (ft)" column. They are used to assure that the ends of the tape are level and to quantify the vertical distance between the suspended tape and the water surface. Water surface readings and horizontal distances are also recorded upstream and downstream of the suspended tape. These observations are used to establish the water surface slope for input into Manning's equation.

The right side of the "Channel Profile Data" section is used to graphically depict the relative locations of the suspended tape and survey level, the direction of streamflow, and any photographic documentation of the field data collection effort. Photographs of the suspended tape are taken looking up, down, and across the stream.

Biologic sampling is summarized in the "Aquatic Sampling Summary" portion of the field form. Biologic data typically consists of a fish sample, collected by electrofishing, and an aquatic invertebrate sample. Captured fish are identified by species and measured to the nearest inch. A species-specific length-frequency distribution is created by placing a hashmark in the appropriate cell of the table as each fish is measured. Aquatic invertebrate

sampling is summarized within the space provided at the bottom of this section.

All other pertinent field data is recorded in the "Comments" section of the field form. This section is often used to record weather conditions, water turbidity, or species-specific biomass estimates. This additional information helps characterize the field data when it is being analyzed in the office.

The "Discharge/Cross Section Notes" portion of the field form is used to record all of the hydraulic measurements associated with the discharge measurement (Figure C). A heading is provided to record the stream name, cross section number, date, edge of water looking downstream, the staging pin reading, and time at the beginning of the stream discharge measurement. The table below the heading is used to record "Features", "Distance From Initial Point", "Width", "Total Vertical Depth From Tape/Instrument", and "Water Depth" channel geometry parameters at each cell vertical. Stream velocity measurements are recorded under the columns labeled "Depth of Observation", "Revolutions", "Time", and "Velocity" for each wet cell. All discharge measurement procedures are as outlined by Buchanan and Somers (1969).

The first and last channel geometry measurements are always taken at the cross section stakes. Channel geometry measurements should also be taken at the grassline-streambank and streambank-waterline intersections and at all distinguishable slope breaks between these two intersection points. The horizontal locations of the grassline-streambank and streambank-waterline intersections are also documented by placing a "G" and a "W" in the appropriate row of the "Features" column of the field form. Grassline is identified at the normal high water line, not flood stage, and is generally located below sedges and other plants that may survive submerged under high flows. The "Features"

column is also used to document the horizontal locations of the two cross section stakes ("S") and any rocks ("R") or other features that may have an impact on the discharge measurement.

In streams with uniform bottom profiles (i.e., sand, cobble, etc.), channel geometry and discharge measurements are taken at fixed intervals within the wetted portion of the channel. The interval is varied in streams with boulder substrates to more accurately reflect changes in the velocity distribution with changes in channel bottom profile. The stream discharge measurement is divided into a minimum of 20 to 30 discharge cells, depending upon wetted stream width, with a minimum cell

width of 0.3 feet. Sufficient measurements are taken to ensure that no more than 10% of the total streamflow occurs within a single discharge cell. Horizontal and vertical distances are taken from the suspended tape and recorded to the nearest tenth of a foot. Stream velocity (ft/sec) within each cell is averaged and recorded.

The bottom of the "Discharge/Cross Section Notes" section is used to summarize the discharge measurement. Space is also provided to record the names of the persons responsible for the field data calculations, the staging pin reading, and time at the end of the stream discharge measurement.

COLORADO WATER
CONSERVATION BOARD

FIELD DATA FOR INSTREAM FLOW DETERMINATIONS

LOCATION INFORMATION

STREAM NAME:		CROSS-SECTION NO.:	
CROSS-SECTION LOCATION			
DATE	OBSERVERS.		
LEGAL DESCRIPTION	% SECTION	SECTION	TOWNSHIP N/S RANGE E/W PM
COUNTY.	WATERSHED	WATER DIVISION	DOW WATER CODE.
MARS	USGS:		
	USFS:		

SUPPLEMENTAL DATA

SAG TAPE SECTION SAME AS DISCHARGE SECTION?	YES / NO	METER TYPE
METER NUMBER.	DATE RATED.	CALIB/SPIN _____ SEC
TAPE WEIGHT _____ LBS/100'		TAPE TENSION _____ LBS
CHANNEL BED MATERIAL SIZE RANGE	PHOTOGRAPHS TAKEN YES/NO	NUMBER OF PHOTOGRAPHS.

CHANNEL PROFILE DATA

STATION	DISTANCE FROM TAPE (ft)	ROD READING (ft)
(X) Tape @ Stake LB	0.0	
(X) Tape w Stake AB	0.0	
(1) WS @ Tape LB/RB	0.0	
(2) WS Upstream		
(3) WS Downstream		
SLOPE		

SKETCH

A hand-drawn sketch of a channel cross-section. A horizontal line represents the ground surface. Below it, a vertical line labeled 'TAPE' connects four points marked with symbols: a circled X at the top, a circle with a dot (station 1), a circle with a dot (station 2), and another circled X at the bottom. The stations are labeled on the left as (X) Tape @ Stake LB, (X) Tape w Stake AB, (1) WS @ Tape LB/RB, (2) WS Upstream, and (3) WS Downstream.

LEGEND:

Stake (X)

Station (1)

Photo (circle with dot)

Direction of Flow →

AQUATIC SAMPLING SUMMARY

STREAM ELECTROFISHED YES/NO	DISTANCE ELECTROFISHED _____ ft	FISH CAUGHT YES/NO	WATER CHEMISTRY SAMPLED YES/NO														
LENGTH - FREQUENCY DISTRIBUTION BY ONE-INCH SIZE GROUPS (1.0-1.9, 2.0-2.9, ETC.)																	
SPECIES/FILL IN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	>15	TOTAL
AQUATIC INSECTS IN STREAM SECTION BY COMMON OR SCIENTIFIC ORDER NAME																	

COMMENTS

FORM #ISF FD 1-85

[illegible]

Office Procedures

The CWCB uses a Lotus 1-2-3 macro, called R2CROSS, to process the field data and model instream hydraulic parameters at streamflows above and below the field-measured discharge. The CWCB relies upon the biologic expertise of the cooperating agencies to interpret the output from R2CROSS and develop an initial, biologic instream flow recommendation. This initial recommendation is designed to address the unique biologic requirements of each stream without regard to water availability. After receiving the cooperating agencies' biologic recommendation, the CWCB staff evaluates stream hydrology to determine whether water is physically available for an instream flow appropriation.

Background on the R2CROSS Methodology

Three instream hydraulic parameters, average depth ($\bar{x}_d$), average velocity ($\bar{x}_v$), and percent wetted perimeter (%WP), are used to develop biologic instream flow recommendations in Colorado. The DOW has determined that by maintaining these three hydraulic parameters at adequate levels across riffle habitat-types, aquatic habitat in pools and runs will also be maintained for most life stages of fish and aquatic invertebrates (Nehring 1979).

The R2CROSS methodology uses Manning's equation to predict $\bar{x}_d$, $\bar{x}_v$, %WP, and other instream hydraulic parameters, at discharges both above and below the field-measured stream discharge. The methodology is both time and labor efficient, requires data from only a single stream transect, and has been found to produce similar results to more data intensive techniques (Nehring 1979) such as the Instream Flow Incremental Methodology (IFIM) developed by the U.S. Fish and Wildlife Service (Bovee 1982).

In 1973, the CWCB staff performed all Manning's equation calculations with a hand-

held calculator. In 1981, the USFS released "*Program Documentation for R2-CROSS-81*" (Weathered et al. 1981). This Fortran-based, mainframe computer program automated the repetitive task of manipulating and recalculating Manning's equation by hand. The CWCB used the USFS version of R2CROSS on the Colorado State University mainframe computer until 1985.

In 1986, the CWCB staff began development of a personal computer version of R2CROSS using the macro capabilities of Lotus 1-2-3. The CWCB found the R2CROSS macro to be advantageous because it ran on a personal computer and it could be customized to the specific needs of the CWCB. The most recent version of R2CROSS is menu-driven (Figure D) and requires very little experience with Lotus 1-2-3. The macro formats the R2CROSS worksheet, initiates data entry, and performs all calculations and printing automatically.

Figures E through K provide an example of R2CROSS output from a typical Colorado stream. Figure E is a "Proof Sheet" that is printed and inspected for data entry errors prior to performing final R2CROSS calculations. Final output consists of a five page printout (Figures F through J). Page one summarizes most of the stream location information, supplemental data, and channel profile data from the field form (Figure F). Page two summarizes the channel geometry/discharge field data set and values computed from the raw field data, including an estimate of Manning's "n" (Figure G). Page three consists of a water line comparison table which the program uses to interpolate the single water surface elevation that results in a calculated cross-sectional area equal to the field-measured cross-sectional area (Figure H). Page four is the staging table that is used by the cooperating agency to develop an initial, biologic instream flow recommendation

(Figure I). The staging table provides estimates of modeled instream hydraulic parameters at stages above and below the measured discharge. Page five summarizes measured and calculated flows, waterlines, and depths (Figure J). It also presents estimates of mean velocity, Manning's "n", water slope, and upper and lower streamflow limits within which the instream flow recommendation should fall. In general, hydraulic models based upon Manning's

equation are most accurate when predicted flows fall within a range of 0.4 to 2.5 times measured flow (Bovee and Milhous 1978; Bovee 1982). Space is also provided for a narrative describing the basis for the initial instream flow recommendation and for the signatures of the personnel involved in making the recommendation. The macro can also be used to generate a plot of the stream cross section (Figure K).

Figure D. The R2CROSS Menu

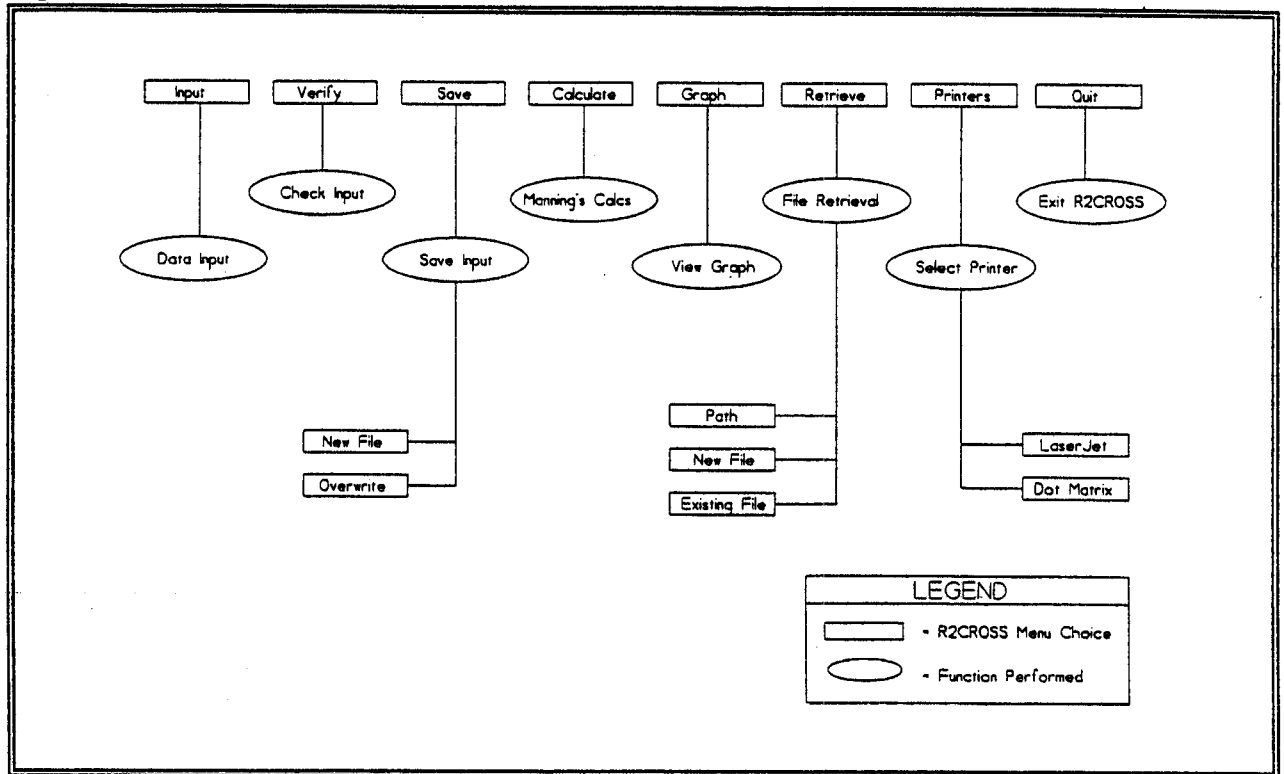


Figure E. R2CROSS proof sheet

LOCATION INFORMATION		PROOF SHEET						
=====		=====						
INPUT DATA		# DATA POINTS= 34						
=====		=====						
STREAM NAME:	IRON CREEK	FEATURE	DIST	VERT DEPTH	WATER DEPTH	VEL	A	Q
XS LOCATION:	100 YDS U/S DWB DIVERSION							TAPE TO WATER
XS NUMBER:	1							
DATE:	10/17/86	S	0.00	1.10	0.00	0.00	0.00	0.00
OBSERVERS:	SEAHOLM, PUTTMAN	1 G	0.50	1.30	0.00	0.00	0.00	0.00
1/4 SEC:			1.00	1.40	0.00	0.00	0.00	0.00
SECTION:	20		2.00	1.80	0.00	0.00	0.00	0.00
TWP:	2S		2.50	1.95	0.00	0.00	0.00	0.00
RANGE:	76W	R	3.00	2.00	0.00	0.00	0.00	0.00
PM:	6TH		3.50	1.90	0.00	0.00	0.00	0.00
COUNTY:	GRAND		4.00	2.45	0.00	0.00	0.00	0.00
WATERSHED:	FRASER		4.50	2.45	0.00	0.00	0.00	0.00
DIVISION:	5	W	5.00	2.60	0.00	0.00	0.00	0.00
DOW CODE:	25482		5.70	3.00	0.40	0.80	0.20	0.16
USGS MAP:	BYERS PEAK		6.00	3.10	0.45	0.45	0.13	0.06
USFS MAP:	ARAPAHOE		6.30	3.00	0.40	1.10	0.12	0.13
SUPPLEMENTAL DATA			6.60	3.00	0.40	0.95	0.12	0.11
=====			6.90	2.95	0.35	0.95	0.11	0.10
TAPE WT:	0.0106		7.20	2.85	0.25	0.70	0.07	0.05
TENSION:	28		7.50	3.10	0.50	0.75	0.15	0.11
CHANNEL PROFILE DATA			7.80	3.10	0.50	0.65	0.15	0.10
=====			8.10	3.10	0.50	0.85	0.15	0.13
SLOPE:	0.0055		8.40	3.20	0.60	0.95	0.18	0.17
			8.70	3.20	0.60	1.10	0.18	0.20
			9.00	3.20	0.60	1.35	0.18	0.24
			9.30	3.15	0.55	1.40	0.16	0.23
			9.60	3.25	0.65	1.50	0.19	0.29
			9.90	3.30	0.70	1.55	0.21	0.33
			10.20	3.30	0.70	1.60	0.21	0.34
			10.50	3.30	0.70	1.25	0.12	0.15
		W	10.55	2.60	0.00	0.00	0.00	0.00
		1 G	11.00	1.30	0.00	0.00	0.00	0.00
			11.50	0.85	0.00	0.00	0.00	0.00
			12.00	0.60	0.00	0.00	0.00	0.00
			12.50	0.55	0.00	0.00	0.00	0.00
			13.00	0.55	0.00	0.00	0.00	0.00
		S	13.50	0.50	0.00	0.00	0.00	0.00
		=====						
		TOTALS						
		2.65 2.91						
		=====						

Figure F. Final output from R2CROSS (Page 1)

```
*****
*          COLORADO WATER CONSERVATION BOARD          *
*    INSTREAM FLOW / NATURAL LAKE LEVEL PROGRAM    *
*          STREAM CROSS-SECTION AND FLOW ANALYSIS      *
*****

LOCATION INFORMATION
=====

STREAM NAME:  IRON CREEK
XS LOCATION:  100 YDS U/S DWB DIVERSION
XS NUMBER:    1

DATE:         1C/17/86
OBSERVERS:    SEAHOLM, PUTTMAN

1/4 SEC:
SECTION:      20
TWP:          2S
RANGE:        76W
PM:           6TH

COUNTY:      GRAND
WATERSHED:    FRASER
DIVISION:     5
DOW CODE:     25482

USGS MAP:     BYERS PEAK
USFS MAP:     ARAPAHOE

SUPPLEMENTAL DATA      *** NOTE ***
=====      Leave TAPE WT and TENSION
                  at defaults for data collected
TAPE WT:        0.0106 with a survey level and rod
TENSION:        28

CHANNEL PROFILE DATA
=====
SLOPE:          0.0055

INPUT DATA CHECKED BY: .....DATE.....
ASSIGNED TO: .....DATE.....
```

Figure G. Final output from R2CROSS (Page 2)

STREAM NAME: IRON CREEK
XS LOCATION: 100 YDS U/S DWB DIVERSION
XS NUMBER: 1

INPUT DATA # DATA POINTS= 34

FEATURE	DIST	VERT DEPTH	WATER DEPTH	VEL
S	0.00	1.10	0.00	0.00
	0.50	1.30	0.00	0.00
1 G	1.00	1.40	0.00	0.00
	2.00	1.80	0.00	0.00
	2.50	1.95	0.00	0.00
	3.00	2.00	0.00	0.00
R	3.50	1.90	0.00	0.00
	4.00	2.45	0.00	0.00
	4.50	2.45	0.00	0.00
W	5.00	2.60	0.00	0.00
	5.70	3.00	0.40	0.80
	6.00	3.10	0.45	0.45
	6.30	3.00	0.40	1.10
	6.60	3.00	0.40	0.95
	6.90	2.95	0.35	0.95
	7.20	2.85	0.25	0.70
	7.50	3.10	0.50	0.75
	7.80	3.10	0.50	0.65
	8.10	3.10	0.50	0.85
	8.40	3.20	0.60	0.95
	8.70	3.20	0.60	1.10
	9.00	3.20	0.60	1.35
	9.30	3.15	0.55	1.40
	9.60	3.25	0.65	1.50
	9.90	3.30	0.70	1.55
	10.20	3.30	0.70	1.60
	10.50	3.30	0.70	1.25
W	10.55	2.60	0.00	0.00
1 G	11.00	1.30	0.00	0.00
	11.50	0.85	0.00	0.00
	12.00	0.60	0.00	0.00
	12.50	0.55	0.00	0.00
	13.00	0.55	0.00	0.00
S	13.50	0.50	0.00	0.00

VALUES COMPUTED FROM RAW FIELD DATA

WETTED PERIM.	WATER DEPTH	AREA (Am)	Q (Qm)	% Q CELL
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.81	0.40	0.20	0.16	5.5%
0.32	0.45	0.13	0.06	2.1%
0.32	0.40	0.12	0.13	4.5%
0.30	0.40	0.12	0.11	3.9%
0.30	0.35	0.11	0.10	3.4%
0.32	0.25	0.07	0.05	1.8%
0.39	0.50	0.15	0.11	3.9%
0.30	0.50	0.15	0.10	3.4%
0.30	0.50	0.15	0.13	4.4%
0.32	0.60	0.18	0.17	5.9%
0.30	0.60	0.18	0.20	6.8%
0.30	0.60	0.18	0.24	8.4%
0.30	0.55	0.16	0.23	7.9%
0.32	0.65	0.19	0.29	10.1%
0.30	0.70	0.21	0.33	11.2%
0.30	0.70	0.21	0.34	11.6%
0.30	0.70	0.12	0.15	5.3%
0.70	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%
0.00	0.00	0.00	0.00	0.0%

TOTALS -----

6.49 0.7 2.65 2.91 100.0%
(Max.)

Manning's n = 0.0552

Figure H. Final output from R2CROSS (Page 3)

STREAM NAME: IRON CREEK
 XS LOCATION: 100 YDS U/S DWB DIVERSION
 XS NUMBER: 1

WATER LINE COMPARISON TABLE

=====

WATER	MEAS	COMP	AREA
LINE	AREA	AREA	ERROR

=====

2.36	2.65	4.21	59.0%
2.38	2.65	4.07	53.9%
2.40	2.65	3.94	48.8%
2.42	2.65	3.81	43.8%
2.44	2.65	3.67	38.8%
2.46	2.65	3.54	33.8%
2.48	2.65	3.42	29.2%
2.50	2.65	3.30	24.7%
2.52	2.65	3.18	20.2%
2.54	2.65	3.07	15.8%
2.56	2.65	2.95	11.4%
2.57	2.65	2.89	9.3%
2.58	2.65	2.84	7.1%
2.59	2.65	2.78	5.0%
2.60	2.65	2.72	2.9%
2.61	2.65	2.67	0.8%
2.62	2.65	2.61	-1.3%
2.63	2.65	2.56	-3.4%
2.64	2.65	2.50	-5.5%
2.65	2.65	2.45	-7.6%
2.66	2.65	2.39	-9.6%
2.68	2.65	2.28	-13.7%
2.70	2.65	2.18	-17.8%
2.72	2.65	2.07	-21.9%
2.74	2.65	1.96	-25.9%
2.76	2.65	1.86	-29.9%
2.78	2.65	1.75	-33.9%
2.80	2.65	1.65	-37.8%
2.82	2.65	1.54	-41.8%
2.84	2.65	1.44	-45.6%
2.86	2.65	1.34	-49.5%

=====

WATERLINE AT ZERO
 AREA ERROR = 2.611

Figure I. Final output from R2CROSS (Page 4)

STREAM NAME: IRON CREEK
XS LOCATION: 100 YDS U/S DWB DIVERSION
XS NUMBER: 1

GL = lowest Grassline elevation corrected for sag

STAGING TABLE *WL* = Waterline corrected for variations in field measured water surface elevations and sag

	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT WET PER (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
GL	1.40	<u>9.27</u>	1.21	1.90	12.09	12.14	100.0%	1.00	24.07	1.99
	1.61	9.38	1.07	1.70	10.08	11.37	93.6%	0.89	18.57	1.84
	1.66	9.23	1.04	1.65	9.61	11.18	92.0%	0.86	17.36	1.81
	1.71	9.09	1.01	1.60	9.15	10.99	90.5%	0.83	16.18	1.77
	1.76	8.95	0.97	1.55	8.70	10.80	89.0%	0.81	15.04	1.73
	1.81	8.80	0.94	1.50	8.26	10.61	87.4%	0.78	13.95	1.69
	1.86	8.62	0.91	1.45	7.82	10.39	85.5%	0.75	12.93	1.65
	1.91	8.41	0.88	1.40	7.40	10.13	83.5%	0.73	11.97	1.62
	1.96	7.90	0.88	1.35	6.99	9.55	78.6%	0.73	11.33	1.62
	2.01	7.16	0.92	1.30	6.61	8.75	72.0%	0.76	10.96	1.66
	2.06	7.10	0.88	1.25	6.26	8.63	71.0%	0.73	10.08	1.61
	2.11	7.04	0.84	1.20	5.90	8.51	70.0%	0.69	9.24	1.57
	2.16	6.97	0.80	1.15	5.55	8.39	69.1%	0.66	8.42	1.52
	2.21	6.91	0.75	1.10	5.21	8.27	68.1%	0.63	7.64	1.47
	2.26	6.85	0.71	1.05	4.86	8.15	67.1%	0.60	6.88	1.42
	2.31	6.79	0.67	1.00	4.52	8.02	66.1%	0.56	6.16	1.36
	2.36	6.72	0.62	0.95	4.18	7.90	65.1%	0.53	5.47	1.31
	2.41	6.66	0.58	0.90	3.85	7.78	64.1%	0.49	4.81	1.25
	2.46	6.09	0.58	0.85	3.52	7.16	58.9%	0.49	4.38	1.24
	2.51	5.91	0.55	0.80	3.22	6.93	57.1%	0.46	3.86	1.20
	2.56	5.72	0.51	0.75	2.93	6.70	55.2%	0.44	3.37	1.15
WL	2.61	5.55	0.48	0.70	2.65	6.48	53.4%	0.41	2.91	1.10
	2.66	5.45	0.43	0.65	2.37	6.33	52.1%	0.37	<u>2.46</u>	<u>1.04</u>
	2.71	5.36	0.39	0.60	2.10	6.18	<u>50.9%</u>	0.34	<u>2.04</u>	<u>0.97</u>
	2.76	5.27	0.35	0.55	1.84	6.03	<u>49.7%</u>	0.30	<u>1.66</u>	0.90
	2.81	5.18	0.30	0.50	1.57	5.88	48.4%	0.27	1.31	0.83
	2.86	5.08	0.26	0.45	1.32	5.72	47.1%	0.23	0.99	0.75
	2.91	4.78	<u>0.22</u>	0.40	1.07	5.33	43.9%	0.20	<u>0.73</u>	0.68
	2.96	4.47	<u>0.19</u>	0.35	0.84	4.94	40.7%	0.17	<u>0.51</u>	0.61
	3.01	3.73	0.17	0.30	0.63	4.11	33.8%	0.15	0.36	0.57
	3.06	3.36	0.13	0.25	0.45	3.66	30.2%	0.12	0.22	0.49
	3.11	2.41	0.12	0.20	0.29	2.63	21.6%	0.11	0.14	0.46
	3.16	2.22	0.08	0.15	0.18	2.39	19.7%	0.07	0.06	0.35
	3.21	1.05	0.08	0.10	0.08	1.15	9.4%	0.07	0.03	0.34
	3.26	0.88	0.04	0.05	0.03	0.93	7.6%	0.04	0.01	0.22

** NOTE**: Bold and underlined text within the Iron Creek staging table was added to facilitate explanation of the procedure for developing biologic instream flow recommendations (see Pages 18-19). Standard R2CROSS staging table printouts will not contain these enhancements.

Figure J. Final output from R2CROSS (Page 5)

STREAM NAME: IRON CREEK
 XS LOCATION: 100 YDS U/S DWB DIVERSION
 XS NUMBER: 1

SUMMARY SHEET

MEASURED FLOW (Q_m) = 2.91 cfs
 CALCULATED FLOW (Q_c) = 2.91 cfs
 $(Q_m - Q_c) / Q_m * 100 = -0.1 \%$

MEASURED WATERLINE (W_{Lm}) = 2.61 ft
 CALCULATED WATERLINE (W_{Lc}) = 2.61 ft
 $(W_{Lm} - W_{Lc}) / W_{Lm} * 100 = -0.1 \%$

MAX MEASURED DEPTH (D_m) = 0.70 ft
 MAX CALCULATED DEPTH (D_c) = 0.70 ft
 $(D_m - D_c) / D_m * 100 = 0.6 \%$

MEAN VELOCITY = 1.10 ft/sec
 MANNING'S n = 0.055
 SLOPE = 0.0055 ft/ft

.4 * Q_m = 1.2 cfs
 2.5 * Q_m = 7.3 cfs

RECOMMENDED INSTREAM FLOW:

=====

FLOW (CFS) PERIOD

=====

=====

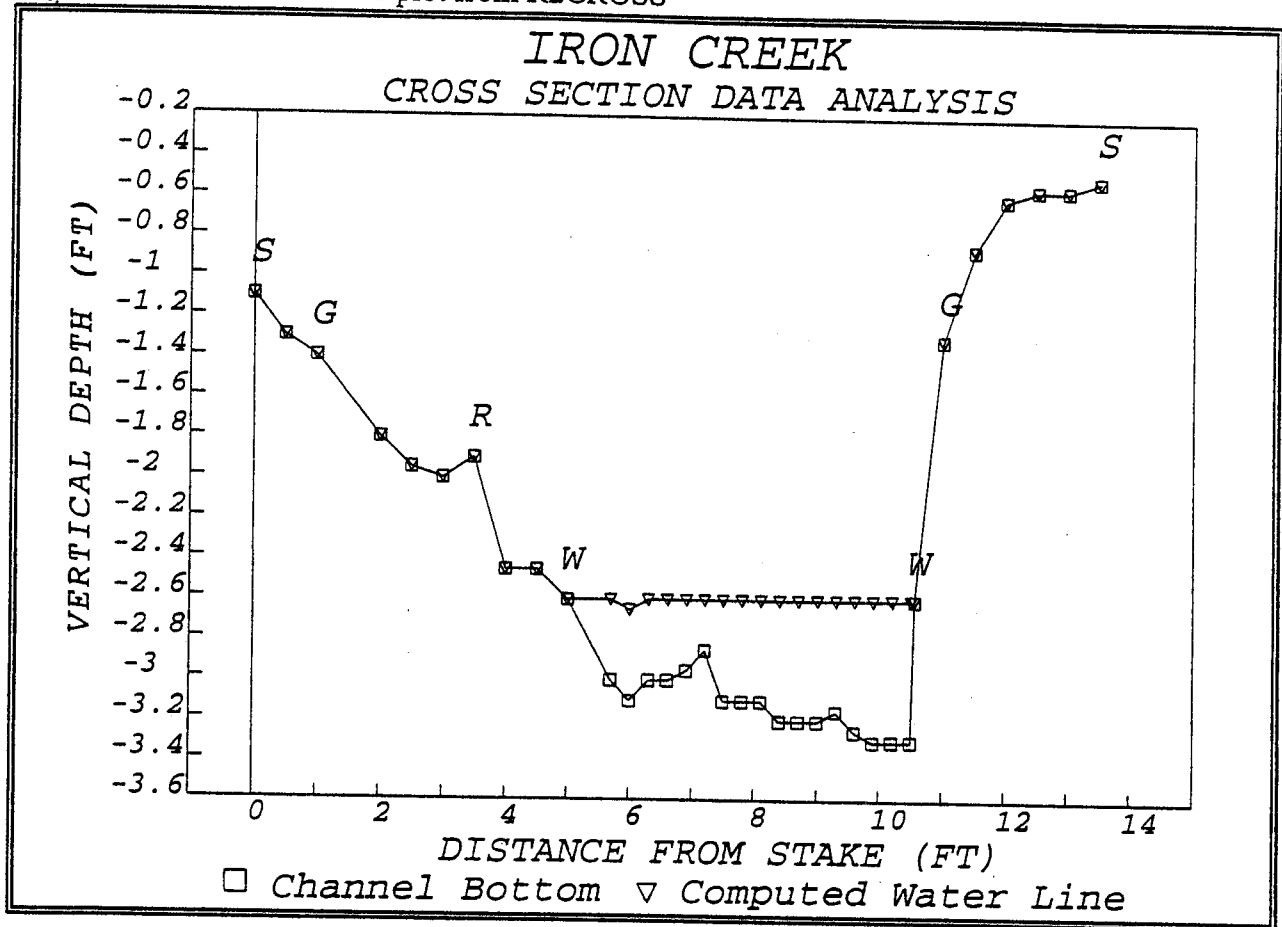
RATIONALE FOR RECOMMENDATION:

=====

RECOMMENDATION BY: AGENCY: DATE:

CWCB REVIEW BY: DATE:

Figure K. Cross section plot from R2CROSS



Biologic Instream Flow Recommendations

When using R2CROSS, biologic instream flow recommendations are based on maintaining three principal hydraulic criteria, $\bar{x}_d$, $\bar{x}_v$, and %WP, at adequate levels across the stream transect (Table 2). The $\bar{x}_d$ and %WP criteria are functions of stream top width and grassline-to-grassline wetted perimeter, respectively. A constant $\bar{x}_v$ of 1 ft/sec is recommended for all streams. The DOW has determined that these three parameters are good indices of flow-related stream habitat quality and that maintenance of these parameters at adequate levels across riffle habitat-types will also result in maintenance of adequate aquatic habitat in pools and runs for most life stages of

fish and aquatic invertebrates (Nehring 1979).

The three critical hydraulic parameters are estimated within the R2CROSS staging table at various levels of discharge (Figure I). Biologic instream flow recommendations are developed by locating the modeled streamflow(s) in the R2CROSS staging table that satisfy the three hydraulic criteria summarized in Table 2. The streamflow that meets two of the three criteria is considered as an initial winter flow recommendation. Initial summer flow recommendations are based upon satisfying all three criteria (Skinner, pers. comm). Aquatic biologists may modify summer and winter flow recommendations

Table 2. Criteria used to determine minimum flow requirements using the R2CROSS single transect method (Nehring 1979)

Stream Top Width (ft) ¹	Average Depth (ft)	Percent Wetted Perimeter (%) ¹	Average Velocity (ft/sec)
1-20	0.2	50	1.0
21-40	0.2-0.4	50	1.0
41-60	0.4-0.6	50-60	1.0
61-100	0.6-1.0	≥ 70	1.0

¹ At bankfull discharge.

based upon biologic considerations such as stream conditions, species composition, and aquatic habitat quality.

These hydraulic criteria can be applied to the R2CROSS staging table from the Iron Creek example (Figure I) to develop an initial biologic instream flow recommendation. In this example, the grassline top width of Iron Creek is 9.97 ft. Therefore, the DOW criteria for an $\bar{x}_d$ of 0.2 feet would be satisfied at a flow of approximately 0.6 cfs. The %WP criterion of 50% would be met at a flow of around 1.75 cfs and an $\bar{x}_v$ of 1 ft/sec at a flow of 2.25 cfs. Based upon this analysis, a winter flow recommendation of 1.75 cfs would meet the $\bar{x}_d$ and %WP criteria and a summer flow recommendation of 2.25 cfs would satisfy all three criteria. These initial recommendations may be adjusted up or down based upon biologic judgment and expertise.

Water Availability Requirements

Once an initial biologic instream flow recommendation has been developed, the CWCB staff must determine whether water is physically available to satisfy the biologic recommendation. The staff uses stream gaging

records to analyze physical water availability whenever possible. In the absence of a gage record, the staff may use standardized hydrologic techniques, such as areal apportionment or synthetic streamflow modeling (Kircher et al. 1985), to estimate physical water availability. The staff may also conduct a review of the State Engineer's water rights tabulation and consult with Division Engineers and District Water Commissioners to determine the effect of senior diversions on a stream reach.

The water availability analyses may lead the CWCB staff to conclude that sufficient water is not available to meet the biologic recommendation. In that situation, the CWCB staff may request that the cooperating agency reconsider its biologic recommendation and determine whether the natural environment can be preserved with the amount of water available. If the natural environment can be preserved with the available water, the instream flow recommendation may be revised to reflect the lower available flow amounts. If the statutory water availability requirement cannot be satisfied, the CWCB must reject the instream flow recommendation.

Appropriating and Protecting an Instream Flow Water Right

On November 10, 1993, the CWCB adopted the "Statement of Basis and Purpose and Rules and Regulations Concerning the Colorado Instream Flow and Natural Lake Level Program." These Rules and Regulations codified existing CWCB procedures for implementing the Instream Flow Program and established procedures for handling acquisition of water, water rights, and interests in water including conditional rights, modification of instream flows, and inundation of instream flow water rights. The CWCB's procedural requirements for appropriating and protecting instream flow water rights are also described in great detail within these Rules and Regulations.

The procedural aspects of appropriating and protecting an instream flow water right are beyond the intended scope of this manuscript. Individuals who are interested in learning more about these procedures are encouraged to obtain a copy of the above-referenced Rules and Regulations from the CWCB.

Summary

In 1973, the Colorado State Legislature vested the CWCB with the authority to appropriate instream flow water rights to preserve the natural environment to a reasonable degree. Since that time, the CWCB has completed instream flow appropriations on approximately 7,982 miles of Colorado streams, and the Instream Flow Program is expanding.

The CWCB has adopted standardized field and office procedures for developing instream flow recommendations. This standardization helps to ensure that each instream flow recommendation is "necessary" and "reasonable", as required by state statute.

R2CROSS is one of the standard methodologies employed by the CWCB to model instream hydraulic parameters. The

CWCB has chosen to use the R2CROSS methodology because it is both time and labor efficient, requiring data from only a single stream transect. It has also been found to produce similar results to more data intensive techniques like the IFIM. The R2CROSS macro is also easy to use and requires very little in the way of computer hardware or software.

Biologic instream flow recommendations based upon output from R2CROSS are designed to maintain $\bar{x}_v$, $\bar{x}_d$, and %WP at critical levels across riffle habitat-types. It is assumed that by maintaining these critical hydraulic parameters across riffles, aquatic habitat in pools and runs is also preserved. In addition to biologic considerations, water must be physically available for the CWCB to file for an instream flow water right.

An instream flow water right requires a coordinated effort between various state and federal agencies, the public, and the CWCB. The culmination of these efforts is a decreed instream flow water right that is held by the CWCB on behalf of the people of Colorado to "preserve the natural environment to a reasonable degree."

The Colorado State Legislature enacted SB 97 in 1973. By "recognizing the need to correlate the activities of mankind with some reasonable preservation of the natural environment" (§ 37-92-102(3), C.R.S. (1990)), the Legislature sought to balance traditional water development with some reasonable protection of Colorado's natural environment. This is not a simple task in the semi-arid Western United States where water is a scarce, and extremely valuable resource. The ongoing success of Colorado's Instream Flow Program assures that coordination between water development and protection of the natural environment will continue -- both now and into the future.

R2CROSS Program Documentation

Program documentation for the R2CROSS macro is divided into four sections. The "Setup and Installation" section describes the hardware and software requirements of the R2CROSS macro and installation of the R2CROSS program on a hard disk drive. The "Iron Creek Example" provides an opportunity for the new user to learn the most common procedures for entering and analyzing typical R2CROSS data sets and to verify that a newly installed version of R2CROSS is operating properly. "The R2CROSS Menu" provides detailed program documentation for each of the menu choices within R2CROSS (Figure D). Instructions for "Terminating and reactivating the R2CROSS macro" are described in the final section.

Appendix A provides a brief description of the "Program Calculations" that are performed within the R2CROSS macro. Rather than emphasizing the technical aspects of these calculations, this appendix is intended to provide a fundamental understanding of the operations being performed within the macro.

Output from the R2CROSS macro was verified against several simple hand-calculated examples. More complex cross sections were verified by comparison with output from the MANSQ option of IFIM (Bovee 1982). Based on this verification process, it is our belief that the instream hydraulic parameters summarized in the R2CROSS staging table are accurate estimations based upon Manning's equation.

To date, the majority of the CWCB's instream flow water rights have been based

upon recommendations from an R2CROSS analysis. The CWCB chose the R2CROSS methodology because it is both time and labor efficient. It has also been shown to produce similar results to more costly techniques for modeling streamflows (Nehring 1979).

The CWCB hopes that the release of the R2CROSS macro will foster a greater understanding of this technical aspect of Colorado's Instream Flow Program. It is intended to be user-friendly. If you have any problems running the macro or questions regarding its operation, please feel free to contact the CWCB staff.

Setup and Installation

The R2CROSS macro runs efficiently on an IBM-compatible 80486 personal computer equipped with a hard disk drive, and DOS 6.0, Windows 3.1, and Lotus 1-2-3 Release 4 for Windows software.

Copying R2CROSS to a Hard Disk Drive

To begin installation of the R2CROSS program, create an R2CROSS subdirectory on your computer's hard drive using the DOS command:

md c:\R2CROSS

and press <ENTER>.

Copy the files from the enclosed diskette into this subdirectory using the DOS command:

copy a:.* c:\R2CROSS.

Press <ENTER> to execute the command.

Loading Lotus 1-2-3 and Retrieving the R2CROSS Macro

To run the R2CROSS macro, load your copy of Lotus 1-2-3 Version 4 for Windows and open the R2CROSS.WK4 file using the Lotus menu commands "File" and "Open". The R2CROSS macro begins with an introductory message screen. Press <ENTER> to continue.

The data entry and data editing routines of the R2CROSS macro were intended to be very user-friendly. In R2CROSS, the <ENTER> key is used to complete the entry of all data within the "Location Information", "Supplemental Data", and "Channel Profile Data" sections of the data input screen (see Figure E). After entering the stream "Slope", the macro moves into the "Input Data" table. The arrow keys are used to complete the entry of all data within the "Input Data" table. After using the arrow keys to complete the entry of all data within the "Input Data" table, simultaneously press "<Ctrl> G" to exit the data entry routine.

After initial data entry, the arrow keys are used to correct and edit all data entry errors, including corrections to the "Location Information", "Supplemental Data", and "Channel Profile Data" (which were initially entered using the <ENTER> key). Table 3 is intended to help clarify the proper use of the <ENTER> key and the arrow keys within the R2CROSS data entry and data editing routines.

Table 3. Data entry and data editing using the <ENTER> key and arrow keys

	Initial data entry	Data correction/ editing
Location Information Supplemental Data Channel Profile Data	<ENTER> key	Arrow keys
Input Data Table	Arrow keys	Arrow keys

The "Iron Creek Example" which follows is a useful exercise. It is intended to familiarize new users with the data entry nuances of the R2CROSS macro and to verify that the newly installed copy of the R2CROSS macro is operating properly. We recommend that new users take a couple of minutes to work through the "Iron Creek Example" in order to gain hands-on experience with the R2CROSS macro prior to entering individual data sets.

Iron Creek Example

Figure E depicts an actual set of R2CROSS field data collected on Iron Creek, a tributary to the Fraser River in Grand County, Colorado. Assuming that the R2CROSS macro has been installed and initiated as described above, highlight the "Printers" menu choice and select either the LaserJet or Dot Matrix menu choice. Other printer-types may require a customized setup (consult your Lotus 1-2-3 reference manual).

In order to ensure that all subsequent data files are stored in the R2CROSS subdirectory, select the "Retrieve" menu choice, choose the "Path" suboption, key-in:

c:\ R2CROSS

and press <ENTER>.

To initiate data entry, select the "Input" menu option. R2CROSS then prompts you to enter the number of data points collected in the stream cross section. Count the number of data points (Iron Creek has 34), key-in this number at the prompt, and press <ENTER>.

Enter the remainder of the data within the "Location Information", "Supplemental Data", and "Channel Profile Data" sections of the R2CROSS macro. Use the <ENTER> key to complete each data entry and move the cursor through each of the data input cells in sequential order. The final use of the <ENTER> key occurs after keying-in the stream "Slope".

After entering the stream "Slope", use the arrow keys to enter all of the "Feature", "Dist", "Vert Depth", "Water Depth", and "Vel" data from the Input Data table of Figure E. The grasslines on each streambank represent a very important piece of information in the R2CROSS analysis. In the Iron Creek example, these grasslines occur at distances of 1.00 and 11.00 feet. It is imperative that these grasslines be identified within R2CROSS by placing the number "1" in the appropriate cell of Column A in the R2CROSS worksheet. This designation

is so important that the R2CROSS macro will not proceed until the two grasslines have been specified. After entering all of the data within the Input Data table, including the two grasslines, simultaneously press "<Ctrl> G" to terminate the data entry routine and return to the main R2CROSS menu.

Select the "Verify" option to print a "Proof Sheet" for comparison with Figure E. If data entry errors are found, return to the "Input" menu option and correct them. When editing data, use the arrow keys to move around the worksheet and correct mistakes. When all data entry errors have been corrected, exit the editing routine by pressing "<Ctrl> G". The data editing routine can be repeated until all data entry errors have been corrected.

Once all data entry errors have been corrected, use the "Save" menu choice to store the input data file to the R2CROSS directory on the hard disk drive. Select the "New File" menu option, type an appropriate eight letter file name for the data set, and press <ENTER>. The file will automatically be saved with a .WK4 file extension. **Caution: do not name the file "R2CROSS".**

Select the "Calculate" option and press <ENTER> to initiate staging table calculations and print the final output from R2CROSS. Verify that the printed output is identical to Figures F through J.

Select the "Graph" option to view the cross section plot. Press <ENTER> to exit the view and print the cross section plot.

Exit the R2CROSS macro by selecting the "Quit" option. Answer "No" to the Lotus prompt to exit R2CROSS and remain in Lotus 1-2-3.

This general procedure can be followed to enter, edit, and analyze almost all R2CROSS datasets. To begin data entry on your own R2CROSS data set, select "Retrieve" a "New file" from the R2CROSS menu.

The R2CROSS Menu

The R2CROSS menu consists of eight main menu choices arranged from left to right across the top of the computer screen (Figure D). Use the arrow keys to move between menu choices and the <ENTER> key to select a highlighted menu choice.

Input

The "Input" menu choice is used to enter data in a new R2CROSS.WK4 worksheet or to correct/edit data in an existing worksheet. As depicted in Table 3, the <ENTER> key is used for the initial entry of the information contained within the "Location Information", "Supplemental Data", and "Channel Profile Data" sections of the field form. The arrow keys are used for the initial entry of the "Discharge/Cross Section Notes" within the "Input Data" table. The arrow keys are also used for all subsequent editing of data. This procedure ensures that the cursor is always located within the appropriate cell of the worksheet during the initial entry of the "Location Information", "Supplemental data" and "Channel Profile Data" (not always a one cell movement) and also allows the greatest flexibility in the initial entry of the discharge notes and subsequent editing of data.

Entering data in a new file

To enter data in a new file:

1. Select the "Input" menu choice.
2. Count the number of data points (cell verticals) collected across the stream channel. Key-in that number and press <ENTER>. R2CROSS automatically sizes the worksheet to the proper number of discharge cells.
3. Once the worksheet has been sized, the macro prompts for the entry of a

"Stream Name". Key-in the "Stream Name" and press the <ENTER> key to complete the data entry. Follow this same procedure for all of the information contained within the "Location Information", "Supplemental Data", and "Channel Profile Data" data entry cells. The final use of the <ENTER> key occurs after the entry of a stream "Slope". The cursor then moves to the upper left corner of the "Input Data" table (cell C50).

4. Use the arrow keys to enter all channel geometry and stream velocity data within the "Input Data" table. Key-in the horizontal distance from the zero stake to the cell vertical in the "Dist" column, vertical distance from the suspended tape to the channel bottom in the "Vert Depth" column, water depth in the "Water Depth" column, and water velocity in the "Vel" column for each cell in the cross section. Use the "Feature" column (Column B) to indicate the horizontal locations of the cross section stakes (S), grasslines (G), waterlines (W), and other features such as rocks (R), etc. Finally, enter a "1" in the appropriate cell of Column A to indicate the location of the grassline/streambank intersection on each streambank. R2CROSS uses the grassline locations to determine bankfull wetted perimeter and top width. These grassline locations are integral to the development of biologic instream flow recommendations in Colorado. The R2CROSS macro will not proceed until the grassline/streambank intersection on each streambank has been depicted with a "1" in Column A of the worksheet.

5. *When all of the field data has been entered in the "Input Data" table, simultaneously press "<Ctrl> G" to exit from the "Input" routine and return to the main R2CROSS menu.*

Editing data in the current worksheet

To correct data entry errors in the current worksheet:

1. *Select the "Input" option.*
2. *Use the arrow keys to edit data. Data editing begins at the top of the "Input Data" table in cell C50. Move the cursor up from cell C50 to edit "Location Information", Supplemental Data", or "Channel Profile Data". Move down to edit data within the "Input Data" table.*
3. *After correcting all data entry errors, simultaneously press "<Ctrl> G" to terminate the "Input" routine and return to the main R2CROSS menu.*

Editing data in an "Existing file"

Previously-saved files can be retrieved, edited and re-run. Use the R2CROSS menu to "Retrieve" an "Existing file" and then following the instructions under "Editing data in the current worksheet" to edit previously-saved data files.

Verify

The "Verify" option is used to initiate R2CROSS discharge calculations and print a proof sheet (Figure E). Prior to running "Verify", be sure that the proper printer has been initialized (see "Printer" menu option).

Printed output consists of the cross section input data, calculated cross-sectional area, and calculated discharge. The proof sheet should be reviewed to verify accurate entry of all field measurements before continuing to the

"Save" option. If data entry errors are discovered, return to the instructions for "Editing data in the current worksheet" and correct the errors. Proceed to "Save" only after all field data has been entered correctly.

Save

Use "Save" to store data input files. Data input files should always be saved prior to running the "Calculate" option because they are generally smaller in size and they can be retrieved, edited, and rerun if necessary. The "Calculate" option can not be run twice on the same file!

Prior to saving data input files, be sure to run the "Retrieve" and "Path" menu options to specify the location of data storage.

There are two suboptions under the "Save" menu choice, "New file" and "Overwrite". Choose your option carefully and do not overwrite the original R2CROSS.WK4 file!

New file

The first suboption, "New file", is used to save a newly created R2CROSS data set. This is accomplished by the following procedure:

1. *Select "Save" and then "New file" from the R2CROSS menu. R2CROSS prompts for the name of a new file.*
2. *Enter a name of up to eight characters and press <ENTER>.*

If a filename is selected that already exists in the default directory, the computer will beep and the file will not be saved. Should this happen, either repeat the above procedure and save under a different file name or go to the "Overwrite" suboption.

Overwrite

The "Overwrite" suboption is designed to overwrite an existing data file. Use the following procedure to perform this task:

1. *Select "Save" and then "Overwrite" from the R2CROSS menu. R2CROSS will list the files in the current directory that you may chose to overwrite.*
2. *Select a file from the list using the arrow keys and overwrite it by pressing <ENTER>. The existing file will be replaced with the current file. Do not select the original R2CROSS.WK4 file!*

Calculate

"Calculate" initiates all staging table calculations and prints a five page data summary (Figures F through Figure J). Be sure that you have saved your input data set and that the proper printer type has been specified prior to running "Calculate". This operation may take several minutes depending upon the speed of your computer. A detailed explanation of the four major calculations performed within R2CROSS can be found in "Appendix A - Program Calculations".

Graph

The "Graph" option allows the user to view and print a cross-section plot of the stream transect (Figure K). The cross section plot is useful for revealing potential problems with the input data set or potential errors in data collection or data entry. Errors, such as misread rod readings on waterlines or ground profiles, are often easily detected on a cross section plot.

Retrieve

The "Retrieve" menu option has three suboptions, "Path", "New file", and "Existing file". These suboptions are used to change the

current file storage path and to retrieve data files.

Path

The "Path" suboption changes the current data storage location. A valid storage path may be any drive and/or directory which is in existence on the computer's hard drive. To select a new path, follow these steps:

1. *Select "Retrieve" and then "Path" from the R2CROSS menu.*
2. *Type in the name of an existing directory on your hard drive and press <Enter>.*

Subsequent files will be stored and retrieved within this directory. In the event that a non-existent path is entered, the computer will beep and return to the main menu. The default directory will remain in effect until a valid path has been entered.

The "Path" suboption choice is not frequently used. It may be appropriate if you wish to organize R2CROSS data from different streams into separate subdirectories. However, file organization can also be accomplished by simply using descriptive file names. If you do decide to create separate directories for your R2CROSS output files, you should copy the files from the R2CROSS diskette into each of these subdirectories so that they can be retrieved when you want to create a new data set.

New file

The "New file" suboption is used to initiate data entry on a new cross section. It erases the current worksheet from the screen and replaces it with a blank R2CROSS.WK4 worksheet. Read the introductory message and press <ENTER> to initiate data entry.

Existing file

The final suboption, "Existing file", retrieves a previously-saved R2CROSS data set from storage. Simply select the file to be retrieved. Select the "Input" command on the R2CROSS menu to edit the dataset. Staging table calculations are initiated by selecting the "Calculate" option. Remember, the "Calculate" option cannot be run twice on the same file.

Printers

LaserJet

Dot Matrix

The "Printers" menu option is used to format R2CROSS output for either a LaserJet or Dot Matrix type printer. The proper printer-type should be selected prior to running the "Verify" or "Calculate" menu options. Use the arrow keys to highlight the proper printer and press the <ENTER> key. Experienced Lotus 1-2-3 users can setup additional printers prior to retrieving the R2CROSS.WK4 worksheet if necessary. Consult a Lotus manual for specific instructions on setting up other types of printers.

Quit

Select the "Quit" menu option and answer "No" to the Lotus prompt to de-activate the R2CROSS macro and return to normal Lotus 1-2-3 operations. De-activating the R2CROSS macro allows for the use of standard Lotus 1-2-3 commands on all unprotected cells within the current data file. The R2CROSS menu can be reactivated by simultaneously

pressing "<Ctrl> M". Alternatively, a new R2CROSS worksheet can be brought up from within Lotus 1-2-3 by retrieving the original R2CROSS.WK4 file from the computer's hard disk drive (see "Installation" section).

Terminating and Reactivating the R2CROSS Macro

Situations may arise where the macro must be terminated during data entry or calculation routines. To terminate the R2CROSS macro and return to the standard Lotus 1-2-3 menu, press <Ctrl><Break>. Then press the <Esc> key several times to clear the Lotus error message screen.

If the R2CROSS macro was terminated due to a data entry error or a problem with the execution of the macro, the integrity of the worksheet may have been compromised. If so, the current worksheet should be erased and a fresh copy of the R2CROSS.WK4 file retrieved from the computer's hard disk drive. The data should definitely be re-entered if the macro failed during the "Calculate" option of R2CROSS. Trying to rerun a compromised dataset may result in additional problems and unreliable output. It is always safer, albeit more time consuming, to start over.

If you do not believe the data in the current worksheet has been compromised, the R2CROSS macro can be re-activated by simultaneously pressing "<Ctrl> M". Macro operation will begin with the standard R2CROSS menu and data entry or calculations may then resume within the existing file.

Literature Cited

- Bovee, K.D. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper No. 12. Washington, DC: U.S. Fish and Wildlife Service (FWS/OBS-82/26). 248pp.
- Bovee, K.D. and R. Milhous. 1978. Hydraulic simulation in instream flow studies: Theory and techniques. Instream Flow Information Paper No. 5. Washington, DC: U.S. Fish and Wildlife Service (FWS/OBS -78/33). 143pp.
- Buchanan, T.J. and W.P. Somers. 1969. Discharge measurements at gaging stations. Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A8. United States Government Printing Office, Washington, D.C. 20402.
- Benson, M.A., and T. Dalrymple. 1967. General field and office procedures for indirect discharge measurements. Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A1. United States Government Printing Office, Washington, D.C. 20402.
- Chow, V.T. 1959. Open-channel hydraulics. McGraw-Hill Book Company, New York. 680p.
- Colorado Water Conservation Board. 1993. Statement of Basis and Purpose and Rules and Regulations Concerning the Colorado Instream Flow and Natural Lake Level Program. Department of Natural Resources. Denver, CO. 80203.
- Grant, G.E., J.E. Duval, G.J. Koerper and J.L. Fogg. 1992. XSPRO: A channel cross-section analyzer. Technical Note 387. Bureau of Land Management. Denver, CO. 80225-0047.
- Kircher, J.E., A.F. Choquette and B.D. Richter. 1985. Estimation of natural streamflow characteristics in western Colorado. Water-Resources Investigations Report 85-4086. United States Geological Survey. Box 25425, Denver Federal Center. Lakewood, CO 80225.
- Laursen, H.I. 1978. Structural analysis. Second edition. New York. McGraw-Hill Book Company.
- Nehring, R.B. 1979. Evaluation of instream flow methods and determination of water quantity needs for streams in the State of Colorado. Colorado Division of Wildlife. Fort Collins, CO.
- Ray, G.A. and W.F. Megahan. 1979. Measuring cross sections using a sag tape: a generalized procedure. USDA Forest Service General Technical Report INT-47. Intermountain Forest and Range Experiment Station. U.S. Department of Agriculture. Ogden, UT. 84401.

Silvey, L. 1976. R-2 Cross Program: A sag-tape method of channel cross section measurement for use with instream flow determinations. United States Department of Agriculture, Forest Service Region 2. 11177 W. 8th Avenue. Lakewood, CO 80225.

Skinner, J. Instream Flow Coordinator. Colorado Division of Wildlife. Personal communication.

Weatherred, J.D., H.L. Silvey and D.J. Pfankuch. 1981. Program documentation for R2-CROSS-81. Watershed Systems Development Group. United States Department of Agriculture, Forest Service. 3825 East Mulberry Street. Fort Collins, CO 80524.

Appendix A - Program Calculations

Some R2CROSS users may be interested in the operation and layout of the Lotus 1-2-3 macro. Figure L depicts the sequence of operations performed within each R2CROSS menu option. Figure M provides the layout of the R2CROSS macro within the Lotus 1-2-3 worksheet. The four major computations performed within the R2CROSS macro are sag-tape corrections, estimation of Manning's "n", calculation of a water line comparison table, and calculation of a staging table.

Sag-Tape Calculations.

Channel geometry measurements that are taken using the sag-tape methodology must be corrected to a level reference. R2CROSS uses catenary curve formulas to compute these corrections from a sagging tape that has been leveled at each end. The use of the catenary curve solution is based on the assumption that the suspended steel tape is analogous to a suspended cable placed under a unidirectionally distributed load (Laursen 1978).

The derivation of the catenary curve solution is beyond the scope of this manuscript. Basically, R2CROSS uses the length of tape in suspension, the tension applied to the tape, and the standard weight of one foot of tape to apply the necessary vertical distance corrections to each cell vertical within the cross section.

When using a level and stadia rod to survey channel geometry, the tape weight and tension defaults, supplied in the original R2CROSS.WK4 worksheet, will simulate an

extremely light tape stretched at very high tension. This results in a sag correction of approximately zero at each cell vertical.

Use of Manning's Equation.

Manning's equation is defined as:

$$Q = \frac{1.486 * A * R^{2/3} * S^{1/2}}{n}$$

where;

Q = discharge (cfs);

A = cross-sectional area (ft²);

R = hydraulic radius (ft);

S = slope (ft/ft); and

n = Manning's "n", a dimensionless coefficient of roughness.

Manning's equation is used in two separate R2CROSS calculations. It is first used within the "Verify" option to provide an initial estimate of Manning's "n" using the rearranged equation:

$$n = \frac{1.486 * A * R^{2/3} * S^{1/2}}{Q}$$

The parameters Q, A, R, and S are calculated from the raw field data and used to solve directly for "n" (Figures G and J). Once estimated, Manning's "n" remains constant throughout the remainder of the streamflow modeling.

Manning's equation is also used within the "Calculate" option to solve for Q at each simulated water surface elevation within the staging table (Table 4).

Calculation of the Water Line Comparison Table.

R2CROSS uses two techniques for estimating cross-sectional area. One estimate is obtained by summing the product of "measured" water depth and cell width for all cells in the cross section (A_m). This technique allows independent water surface elevations within each cell and provides the most accurate estimate of cross-sectional area at the time the field measurement was made. However, this technique cannot be used to simulate a single, flat water surface elevation at computer-modeled stream discharges.

The second technique used to estimate cross-sectional area involves projecting a single water surface elevation across the stream channel. Channel bottom elevations are subtracted from this projected water surface elevation to obtain a "computed" water depth at each cell vertical. Cross-sectional area is obtained by summing the product of the "computed" water depth and cell width at each cell vertical (A_c). This technique constrains the water surface to a flat plane and is useful for simulating discharges above and below the field-measured discharge.

The water line comparison table (Figure H) iteratively calculates 31 separate estimates of A_c , using projected waterlines ranging from

0.25 feet above to 0.25 feet below the mean waterline measured in the field. The single water surface elevation that results in A_c equal to A_m is interpolated from the water line comparison table and is used in the staging table as the best estimate of the waterline at the field-measured discharge.

Calculation of the Staging Table.

The final product of the R2CROSS macro is the staging table (Figure I). In addition to the three critical biologic criteria ($\bar{x}_d$, %WP, and $\bar{x}_v$), R2CROSS also calculates incremental estimates of top width (TW), maximum depth (D_{max}), cross-sectional area (A), wetted perimeter (WP), hydraulic radius (R), and flow (Q) at a number of waterline elevations. The upper limit of the model occurs at bankfull discharge which is defined as the lower of the two grassline elevations measured in the field. The lower limit is either 1.75 feet below the waterline calculated in the water line comparison table or stage of zero flow (the lowest field-measured channel profile), whichever is higher in elevation. The formulae for each of the parameters estimated in the staging table are summarized in Table 4.

Figure L. Sequence of operations performed by R2CROSS macro

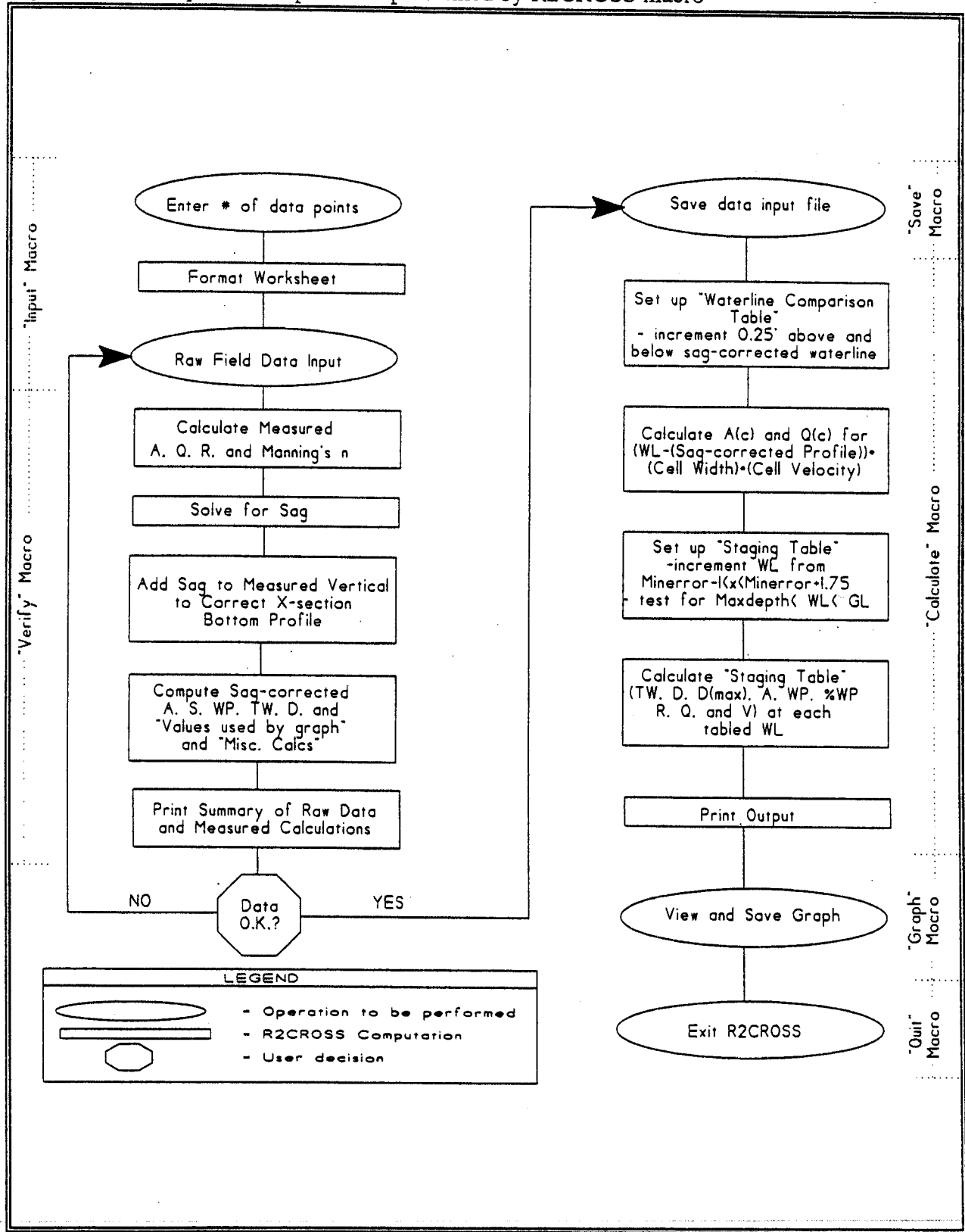


Figure M. Lotus 1-2-3 worksheet layout for R2CROSS macro

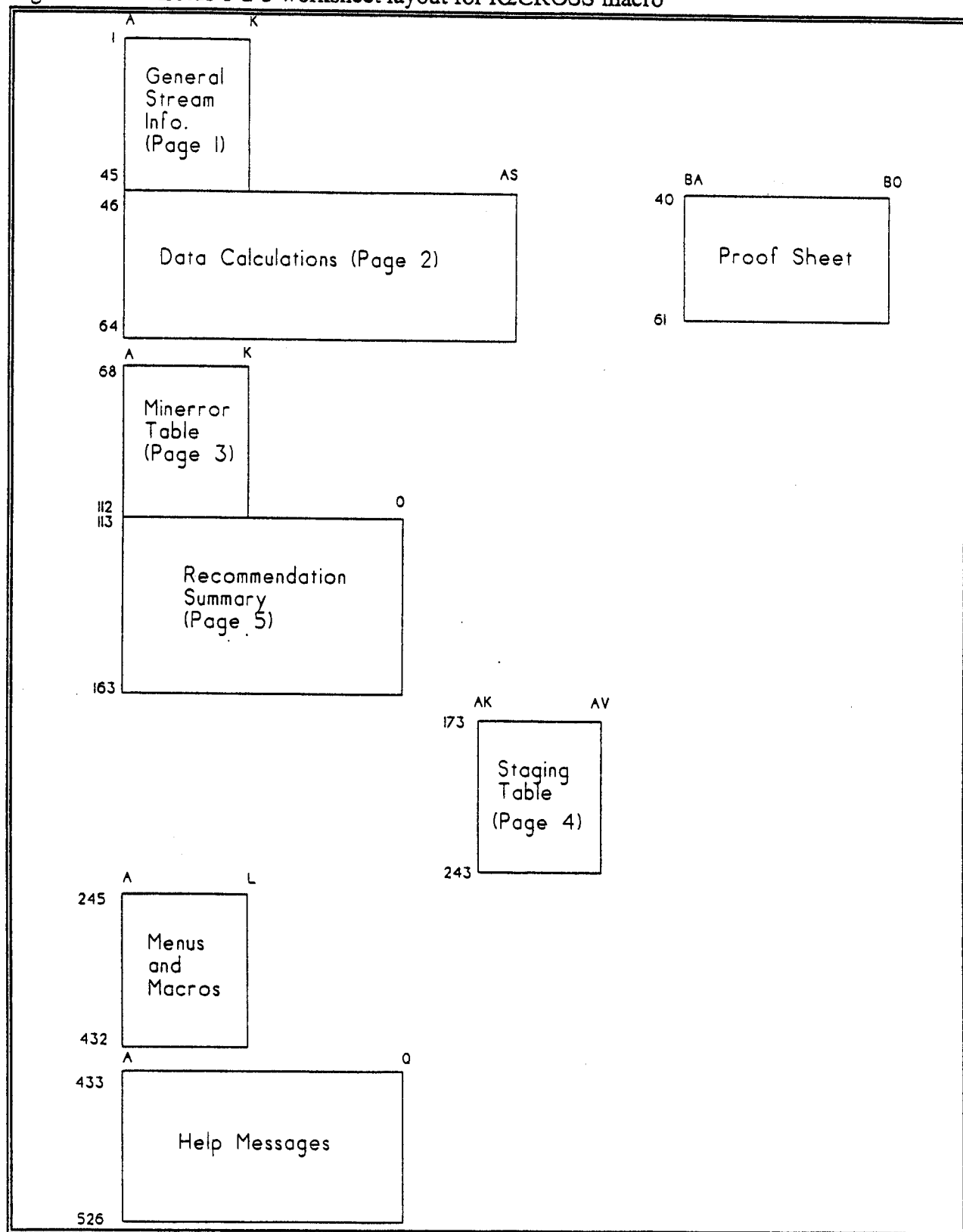


Table 4. Hydraulic Formulas used in R2CROSS staging table

Parameter	Formula
Top Width (TW)	$\sum_{i=1}^n TW_i$
Average Depth ($\bar{x}_d$)	$\frac{A}{TW}$
Maximum Depth (D_{max})	$\underset{i=1}{\overset{n}{MAX}}(D_i)$
Area (A)	$\sum_{i=1}^n A_i$
Wetted Perimeter (WP)	$\sum_{i=1}^n WP_i$
Percent Wetted Perimeter (%WP)	$\frac{WP}{Bankfull\ WP} * 100$
Hydraulic Radius (R)	$\frac{A}{WP}$
Flow (Q)	$\frac{1.486 * A * R^{\frac{2}{3}} * S^{\frac{1}{2}}}{n}$
Average Velocity ($\bar{x}_v$)	$\frac{Q}{A}$

APPENDIX – H

STAGING TABLE - SITE X1

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
30.12744	101.75	94.57	7.18	79.29	2.89	4.45	229.21	81.58	100.0%	2.81	
17.60234	92.72	9.03	56.26	1.90	2.60	106.84	57.25	70.2%	1.87	455.04	4.26
17.26382	92.67	9.08	56.04	1.86	2.55	104.03	56.99	69.9%	1.83	436.57	4.20
16.9253	92.62	9.13	55.82	1.81	2.50	101.23	56.74	69.5%	1.78	418.50	4.13
16.58677	92.57	9.18	55.59	1.77	2.45	98.45	56.48	69.2%	1.74	400.84	4.07
16.24825	92.52	9.23	55.37	1.73	2.40	95.67	56.22	68.9%	1.70	383.58	4.01
15.90972	92.47	9.28	55.15	1.68	2.35	92.91	55.96	68.6%	1.66	366.73	3.95
15.5712	92.42	9.33	54.93	1.64	2.30	90.16	55.70	68.3%	1.62	350.28	3.89
15.23268	92.37	9.38	54.70	1.60	2.25	87.42	55.44	68.0%	1.58	334.23	3.82
14.89415	92.32	9.43	54.48	1.55	2.20	84.69	55.18	67.6%	1.53	318.58	3.76
14.55563	92.27	9.48	54.26	1.51	2.15	81.97	54.92	67.3%	1.49	303.32	3.70
14.2171	92.22	9.53	54.03	1.47	2.10	79.26	54.66	67.0%	1.45	288.47	3.64
13.87858	92.17	9.58	53.81	1.42	2.05	76.57	54.40	66.7%	1.41	274.01	3.58
13.54006	92.12	9.63	53.59	1.38	2.00	73.88	54.14	66.4%	1.36	259.94	3.52
13.20153	92.07	9.68	53.36	1.33	1.95	71.21	53.88	66.0%	1.32	246.27	3.46
12.86301	92.02	9.73	53.14	1.29	1.90	68.55	53.62	65.7%	1.28	232.99	3.40
12.52448	91.97	9.78	52.92	1.25	1.85	65.89	53.36	65.4%	1.23	220.10	3.34
12.18596	91.92	9.83	52.69	1.20	1.80	63.25	53.10	65.1%	1.19	207.60	3.28
11.84743	91.87	9.88	52.47	1.16	1.75	60.63	52.84	64.8%	1.15	195.49	3.22
11.50891	91.82	9.93	52.25	1.11	1.70	58.01	52.58	64.5%	1.10	183.76	3.17
11.17039	91.77	9.98	52.02	1.06	1.65	55.40	52.32	64.1%	1.06	172.42	3.11
10.83186	91.72	10.03	51.80	1.02	1.60	52.80	52.06	63.8%	1.01	161.46	3.06
10.49334	91.67	10.08	51.55	0.97	1.55	50.22	51.79	63.5%	0.97	150.88	3.00
10.15481	91.62	10.13	51.30	0.93	1.50	47.65	51.52	63.2%	0.92	140.68	2.95
9.816291	91.57	10.18	51.05	0.88	1.45	45.09	51.25	62.8%	0.88	130.86	2.90
9.477767	91.52	10.23	50.80	0.84	1.40	42.54	50.98	62.5%	0.83	121.42	2.85
9.139243	91.47	10.28	50.55	0.79	1.35	40.01	50.70	62.2%	0.79	112.35	2.81
8.800719	91.42	10.33	50.30	0.75	1.30	37.49	50.43	61.8%	0.74	103.66	2.76
8.462195	91.37	10.38	49.40	0.71	1.25	35.00	49.53	60.7%	0.71	95.33	2.72
8.123671	91.32	10.43	48.50	0.67	1.20	32.55	48.62	59.6%	0.67	87.38	2.68
7.785147	91.27	10.48	47.58	0.63	1.15	30.15	47.70	58.5%	0.63	79.79	2.65
7.446623	91.22	10.53	46.67	0.60	1.10	27.79	46.78	57.3%	0.59	72.57	2.61
7.108098	91.17	10.58	45.62	0.56	1.05	25.48	45.73	56.1%	0.56	65.71	2.58
6.769574	91.12	10.63	44.58	0.52	1.00	23.23	44.68	54.8%	0.52	59.21	2.55
6.43105	91.07	10.68	43.54	0.48	0.95	21.03	43.64	53.5%	0.48	53.07	2.52
6.092526	91.02	10.73	42.50	0.44	0.90	18.88	42.59	52.2%	0.44	47.29	2.51
5.754002	90.97	10.78	39.37	0.43	0.85	16.83	39.46	48.4%	0.43	41.86	2.49
5.415478	90.92	10.83	37.91	0.39	0.80	14.90	38.00	46.6%	0.39	36.78	2.47
5.076954	90.87	10.88	34.71	0.38	0.75	13.08	34.78	42.6%	0.38	32.04	2.45
4.73843	90.82	10.93	29.00	0.39	0.70	11.43	29.07	35.6%	0.39	27.66	2.42
4.399906	90.77	10.98	28.00	0.36	0.65	10.00	28.07	34.4%	0.36	23.61	2.36
4.061382	90.72	11.03	27.00	0.32	0.60	8.63	27.06	33.2%	0.32	19.90	2.31
3.722858	90.67	11.08	26.00	0.28	0.55	7.30	26.06	31.9%	0.28	16.53	2.26
3.384334	90.62	11.13	24.67	0.24	0.50	6.03	24.72	30.3%	0.24	13.49	2.24
3.04581	90.57	11.18	23.33	0.21	0.45	4.83	23.38	28.7%	0.21	10.77	2.23
2.707286	90.52	11.23	21.67	0.17	0.40	3.71	21.71	26.6%	0.17	8.38	2.26
2.368762	90.47	11.28	20.21	0.13	0.35	2.66	20.25	24.8%	0.13	6.30	2.37
2.030238	90.42	11.33	16.25	0.10	0.30	1.69	16.29	20.0%	0.10	4.53	2.69
1.691714	90.37	11.38	10.84	0.09	0.25	1.01	10.86	13.3%	0.09	3.07	3.04
1.35319	90.32	11.43	5.42	0.11	0.20	0.60	5.43	6.7%	0.11	1.91	3.16
1.014666	90.27	11.48	4.38	0.08	0.15	0.36	4.39	5.4%	0.08	1.03	2.87
0.676142	90.22	11.53	3.33	0.05	0.10	0.17	3.34	4.1%	0.05	0.43	2.60
0.337618	90.17	11.58	1.67	0.03	0.05	0.04	1.67	2.0%	0.02	0.10	2.36
-0.00091	90.12	11.63	0.00	#DIV/0!	0.00	0.00	0.00	0.0%	#DIV/0!		

STAGING TABLE - SITE X2

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
19.09044	95.71	5.21	96.97	3.16	6.06	306.46	102.53	100.0%	2.99	2984.38	9.74
9.665672	92.95	7.97	61.42	1.92	3.30	117.97	63.93	62.4%	1.85	470.91	3.99
9.494907	92.90	8.02	61.29	1.87	3.25	114.90	63.74	62.2%	1.80	448.68	3.90
9.324142	92.85	8.07	61.16	1.83	3.20	111.84	63.55	62.0%	1.76	427.12	3.82
9.153377	92.80	8.12	61.03	1.78	3.15	108.78	63.37	61.8%	1.72	406.23	3.73
8.982612	92.75	8.17	60.90	1.74	3.10	105.74	63.18	61.6%	1.67	385.99	3.65
8.811847	92.70	8.22	60.77	1.69	3.05	102.69	62.99	61.4%	1.63	366.41	3.57
8.641082	92.65	8.27	60.64	1.64	3.00	99.66	62.80	61.3%	1.59	347.46	3.49
8.470317	92.60	8.32	60.51	1.60	2.95	96.63	62.62	61.1%	1.54	329.15	3.41
8.299552	92.55	8.37	60.38	1.55	2.90	93.61	62.43	60.9%	1.50	311.45	3.33
8.128787	92.50	8.42	60.25	1.50	2.85	90.59	62.24	60.7%	1.46	294.37	3.25
7.958022	92.45	8.47	60.12	1.46	2.80	87.58	62.05	60.5%	1.41	277.90	3.17
7.787256	92.40	8.52	59.99	1.41	2.75	84.58	61.86	60.3%	1.37	262.01	3.10
7.616491	92.35	8.57	59.86	1.36	2.70	81.58	61.68	60.2%	1.32	246.72	3.02
7.445726	92.30	8.62	59.73	1.32	2.65	78.60	61.49	60.0%	1.28	232.00	2.95
7.274961	92.25	8.67	59.60	1.27	2.60	75.61	61.30	59.8%	1.23	217.84	2.88
7.104196	92.20	8.72	59.46	1.22	2.55	72.64	61.11	59.6%	1.19	204.25	2.81
6.933431	92.15	8.77	59.33	1.17	2.50	69.67	60.92	59.4%	1.14	191.20	2.74
6.762666	92.10	8.82	59.20	1.13	2.45	66.70	60.74	59.2%	1.10	178.69	2.68
6.591901	92.05	8.87	59.07	1.08	2.40	63.75	60.55	59.1%	1.05	166.72	2.62
6.421136	92.00	8.92	58.94	1.03	2.35	60.80	60.36	58.9%	1.01	155.26	2.55
6.250371	91.95	8.97	58.81	0.98	2.30	57.85	60.17	58.7%	0.96	144.31	2.49
6.079606	91.90	9.02	58.68	0.94	2.25	54.91	59.99	58.5%	0.92	133.86	2.44
5.908841	91.85	9.07	58.56	0.89	2.20	51.98	59.80	58.3%	0.87	123.90	2.38
5.738076	91.80	9.12	58.43	0.84	2.15	49.06	59.62	58.1%	0.82	114.43	2.33
5.567311	91.75	9.17	58.31	0.79	2.10	46.14	59.44	58.0%	0.78	105.42	2.28
5.396546	91.70	9.22	57.54	0.75	2.05	43.24	58.63	57.2%	0.74	96.88	2.24
5.225781	91.65	9.27	56.73	0.71	2.00	40.39	57.80	56.4%	0.70	88.79	2.20
5.055016	91.60	9.32	56.43	0.67	1.95	37.56	57.47	56.1%	0.65	81.13	2.16
4.884251	91.55	9.37	56.13	0.62	1.90	34.74	57.15	55.7%	0.61	73.91	2.13
4.713486	91.50	9.42	55.83	0.57	1.85	31.94	56.82	55.4%	0.56	67.11	2.10
4.542721	91.45	9.47	55.54	0.53	1.80	29.16	56.50	55.1%	0.52	60.72	2.08
4.371956	91.40	9.52	54.01	0.49	1.75	26.42	54.94	53.6%	0.48	54.72	2.07
4.201191	91.35	9.57	45.69	0.52	1.70	23.86	46.60	45.4%	0.51	49.11	2.06
4.030426	91.30	9.62	43.01	0.50	1.65	21.64	43.89	42.8%	0.49	43.89	2.03
3.859661	91.25	9.67	40.34	0.48	1.60	19.55	41.17	40.2%	0.47	39.02	2.00
3.688896	91.20	9.72	38.00	0.46	1.55	17.59	38.80	37.8%	0.45	34.51	1.96
3.518131	91.15	9.77	33.37	0.47	1.50	15.81	34.14	33.3%	0.46	30.35	1.92
3.347366	91.10	9.82	32.27	0.44	1.45	14.17	33.00	32.2%	0.43	26.52	1.87
3.176601	91.05	9.87	28.16	0.45	1.40	12.58	28.87	28.2%	0.44	23.01	1.83
3.005836	91.00	9.92	26.81	0.42	1.35	11.21	27.48	26.8%	0.41	19.80	1.77
2.835071	90.95	9.97	25.49	0.39	1.30	9.90	26.13	25.5%	0.38	16.90	1.71
2.664306	90.90	10.02	19.82	0.44	1.25	8.77	20.43	19.9%	0.43	14.28	1.63
2.493541	90.85	10.07	14.60	0.54	1.20	7.83	15.18	14.8%	0.52	11.93	1.52
2.322776	90.80	10.12	12.38	0.58	1.15	7.16	12.93	12.6%	0.55	9.84	1.37
2.152011	90.75	10.17	10.15	0.65	1.10	6.59	10.67	10.4%	0.62	8.00	1.21
1.981246	90.70	10.22	9.93	0.61	1.05	6.09	10.42	10.2%	0.58	6.39	1.05
1.810481	90.65	10.27	9.71	0.58	1.00	5.60	10.17	9.9%	0.55	5.00	0.89
1.639716	90.60	10.32	9.50	0.54	0.95	5.12	9.93	9.7%	0.52	3.83	0.75
1.46895	90.55	10.37	9.28	0.50	0.90	4.65	9.68	9.4%	0.48	2.84	0.61
1.298185	90.50	10.42	9.06	0.46	0.85	4.19	9.44	9.2%	0.44	2.03	0.48
1.12742	90.45	10.47	8.84	0.42	0.80	3.75	9.19	9.0%	0.41	1.38	0.37
0.956655	90.40	10.52	8.63	0.38	0.75	3.31	8.95	8.7%	0.37	0.89	0.27
0.78589	90.35	10.57	8.41	0.34	0.70	2.88	8.70	8.5%	0.33	0.52	0.18
0.615125	90.30	10.62	8.19	0.30	0.65	2.47	8.46	8.2%	0.29	0.27	0.11
0.44436	90.25	10.67	7.97	0.26	0.60	2.06	8.21	8.0%	0.25	0.11	0.05
0.273595	90.20	10.72	7.76	0.22	0.55	1.67	7.97	7.8%	0.21	0.03	0.02

STAGING TABLE - SITE X3

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
11.29152	100.94	5.84	79.80	2.84	4.45	226.59	81.56	100.0%	2.78	2866.45	12.65
7.031182	93.42	7.52	59.34	1.85	2.77	109.78	60.27	73.9%	1.82	604.96	5.51
6.904311	93.37	7.57	58.73	1.82	2.72	106.83	59.63	73.1%	1.79	569.84	5.33
6.777439	93.32	7.62	58.12	1.79	2.67	103.91	59.00	72.3%	1.76	536.17	5.16
6.650568	93.27	7.67	57.51	1.76	2.62	101.02	58.37	71.6%	1.73	503.91	4.99
6.523697	93.22	7.72	56.90	1.73	2.57	98.16	57.73	70.8%	1.70	473.02	4.82
6.396825	93.17	7.77	56.29	1.69	2.52	95.33	57.10	70.0%	1.67	443.47	4.65
6.269954	93.12	7.82	55.68	1.66	2.47	92.53	56.46	69.2%	1.64	415.24	4.49
6.143082	93.07	7.87	55.07	1.63	2.42	89.76	55.83	68.5%	1.61	388.28	4.33
6.016211	93.02	7.92	54.47	1.60	2.37	87.02	55.20	67.7%	1.58	362.56	4.17
5.88934	92.97	7.97	53.85	1.57	2.32	84.31	54.56	66.9%	1.55	338.05	4.01
5.762468	92.92	8.02	53.24	1.53	2.27	81.64	53.92	66.1%	1.51	314.71	3.86
5.635597	92.87	8.07	52.63	1.50	2.22	78.99	53.29	65.3%	1.48	292.52	3.70
5.508726	92.82	8.12	52.02	1.47	2.17	76.37	52.65	64.6%	1.45	271.45	3.55
5.381854	92.77	8.17	51.40	1.44	2.12	73.79	52.01	63.8%	1.42	251.45	3.41
5.254983	92.72	8.22	50.79	1.40	2.07	71.23	51.38	63.0%	1.39	232.50	3.26
5.128112	92.67	8.27	50.18	1.37	2.02	68.71	50.74	62.2%	1.35	214.57	3.12
5.00124	92.62	8.32	49.57	1.34	1.97	66.22	50.10	61.4%	1.32	197.62	2.98
4.874369	92.57	8.37	48.95	1.30	1.92	63.75	49.47	60.7%	1.29	181.63	2.85
4.747498	92.52	8.42	48.34	1.27	1.87	61.32	48.83	59.9%	1.26	166.56	2.72
4.620626	92.47	8.47	47.73	1.23	1.82	58.92	48.19	59.1%	1.22	152.39	2.59
4.493755	92.42	8.52	47.12	1.20	1.77	56.55	47.56	58.3%	1.19	139.07	2.46
4.366884	92.37	8.57	46.52	1.17	1.72	54.21	46.93	57.5%	1.16	126.59	2.34
4.240012	92.32	8.62	45.92	1.13	1.67	51.90	46.30	56.8%	1.12	114.90	2.21
4.113141	92.27	8.67	45.32	1.09	1.62	49.62	45.67	56.0%	1.09	103.99	2.10
3.986269	92.22	8.72	44.90	1.05	1.57	47.36	45.24	55.5%	1.05	93.83	1.98
3.859398	92.17	8.77	44.49	1.01	1.52	45.13	44.82	55.0%	1.01	84.37	1.87
3.732527	92.12	8.82	44.09	0.97	1.47	42.91	44.40	54.4%	0.97	75.60	1.76
3.605655	92.07	8.87	43.68	0.93	1.42	40.72	43.98	53.9%	0.93	67.48	1.66
3.478784	92.02	8.92	43.27	0.89	1.37	38.54	43.56	53.4%	0.88	59.99	1.56
3.351913	91.97	8.97	42.86	0.85	1.32	36.39	43.13	52.9%	0.84	53.10	1.46
3.225041	91.92	9.02	42.46	0.81	1.27	34.26	42.71	52.4%	0.80	46.78	1.37
3.09817	91.87	9.07	42.05	0.76	1.22	32.14	42.29	51.9%	0.76	41.01	1.28
2.971299	91.82	9.12	41.51	0.72	1.17	30.05	41.74	51.2%	0.72	35.74	1.19
2.844427	91.77	9.17	40.88	0.68	1.12	27.99	41.10	50.4%	0.68	30.97	1.11
2.717556	91.72	9.22	40.24	0.65	1.07	25.97	40.45	49.6%	0.64	26.66	1.03
2.590685	91.67	9.27	39.61	0.61	1.02	23.97	39.81	48.8%	0.60	22.79	0.95
2.463813	91.62	9.32	38.97	0.56	0.97	22.01	39.16	48.0%	0.56	19.32	0.88
2.336942	91.57	9.37	38.34	0.52	0.92	20.07	38.51	47.2%	0.52	16.24	0.81
2.210071	91.52	9.42	37.71	0.48	0.87	18.17	37.87	46.4%	0.48	13.52	0.74
2.083199	91.47	9.47	37.07	0.44	0.82	16.30	37.22	45.6%	0.44	11.14	0.68
1.956328	91.42	9.52	36.15	0.40	0.77	14.47	36.29	44.5%	0.40	9.06	0.63
1.829456	91.37	9.57	35.02	0.36	0.72	12.69	35.15	43.1%	0.36	7.27	0.57
1.702585	91.32	9.62	33.31	0.33	0.67	10.97	33.43	41.0%	0.33	5.74	0.52
1.575714	91.27	9.67	31.94	0.29	0.62	9.35	32.05	39.3%	0.29	4.45	0.48
1.448842	91.22	9.72	29.99	0.26	0.57	7.79	30.09	36.9%	0.26	3.38	0.43
1.321971	91.17	9.77	27.19	0.23	0.52	6.36	27.27	33.4%	0.23	2.50	0.39
1.1951	91.12	9.82	21.42	0.24	0.47	5.17	21.50	26.4%	0.24	1.80	0.35
1.068228	91.07	9.87	20.42	0.20	0.42	4.13	20.49	25.1%	0.20	1.24	0.30
0.941357	91.02	9.92	18.27	0.17	0.37	3.15	18.33	22.5%	0.17	0.82	0.26
0.814486	90.97	9.97	15.27	0.15	0.32	2.31	15.33	18.8%	0.15	0.51	0.22
0.687614	90.92	10.02	10.65	0.16	0.27	1.67	10.70	13.1%	0.16	0.29	0.17
0.560743	90.87	10.07	9.18	0.13	0.22	1.19	9.23	11.3%	0.13	0.15	0.13
0.433872	90.82	10.12	7.77	0.10	0.17	0.76	7.81	9.6%	0.10	0.06	0.09
0.307	90.77	10.17	5.94	0.07	0.12	0.41	5.97	7.3%	0.07	0.02	0.05
0.180129	90.72	10.22	4.11	0.04	0.07	0.16	4.12	5.1%	0.04	0.00	0.02
0.053258	90.67	10.27	1.41	0.01	0.02	0.01	1.41	1.7%	0.01	0.00	0.00

STAGING TABLE - SITE X4

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
18.28724	103.18	7.63	103.21	1.94	3.46	200.67	105.41	100.0%	1.90	1430.11	7.13
12.41934	94.44	8.74	77.47	1.30	2.35	100.37	78.76	74.7%	1.27	543.56	5.42
12.15507	94.39	8.79	76.31	1.26	2.30	96.52	77.56	73.6%	1.24	515.10	5.34
11.8908	94.34	8.84	75.16	1.23	2.25	92.74	76.36	72.4%	1.21	487.56	5.26
11.62653	94.29	8.89	74.00	1.20	2.20	89.01	75.16	71.3%	1.18	460.92	5.18
11.36225	94.24	8.94	72.84	1.17	2.15	85.34	73.96	70.2%	1.15	435.17	5.10
11.09798	94.19	8.99	71.68	1.14	2.10	81.72	72.76	69.0%	1.12	410.31	5.02
10.83371	94.14	9.04	70.52	1.11	2.05	78.17	71.56	67.9%	1.09	386.32	4.94
10.56944	94.09	9.09	69.36	1.08	2.00	74.67	70.36	66.7%	1.06	363.19	4.86
10.30517	94.04	9.14	68.20	1.04	1.95	71.23	69.16	65.6%	1.03	340.91	4.79
10.0409	93.99	9.19	67.04	1.01	1.90	67.85	67.96	64.5%	1.00	319.47	4.71
9.776631	93.94	9.24	65.88	0.98	1.85	64.53	66.76	63.3%	0.97	298.86	4.63
9.51236	93.89	9.29	64.72	0.95	1.80	61.26	65.56	62.2%	0.93	279.07	4.56
9.24809	93.84	9.34	63.56	0.91	1.75	58.06	64.36	61.1%	0.90	260.09	4.48
8.983819	93.79	9.39	62.40	0.88	1.70	54.91	63.16	59.9%	0.87	241.91	4.41
8.719549	93.74	9.44	61.11	0.85	1.65	51.82	61.82	58.6%	0.84	224.51	4.33
8.455278	93.69	9.49	59.82	0.82	1.60	48.80	60.49	57.4%	0.81	207.88	4.26
8.191007	93.64	9.54	58.53	0.78	1.55	45.84	59.15	56.1%	0.77	192.02	4.19
7.926737	93.59	9.59	57.23	0.75	1.50	42.94	57.81	54.8%	0.74	176.90	4.12
7.662466	93.54	9.64	55.94	0.72	1.45	40.11	56.47	53.6%	0.71	162.53	4.05
7.398196	93.49	9.69	54.65	0.68	1.40	37.35	55.14	52.3%	0.68	148.87	3.99
7.133925	93.44	9.74	53.35	0.65	1.35	34.65	53.80	51.0%	0.64	135.93	3.92
6.869654	93.39	9.79	52.31	0.61	1.30	32.01	52.73	50.0%	0.61	123.69	3.86
6.605384	93.34	9.84	48.94	0.60	1.25	29.48	49.34	46.8%	0.60	112.14	3.80
6.341113	93.29	9.89	47.88	0.57	1.20	27.06	48.26	45.8%	0.56	101.25	3.74
6.076842	93.24	9.94	44.82	0.55	1.15	24.74	45.18	42.9%	0.55	91.03	3.68
5.812572	93.19	9.99	39.75	0.57	1.10	22.57	40.09	38.0%	0.56	81.46	3.61
5.548301	93.14	10.04	38.69	0.53	1.05	20.61	39.01	37.0%	0.53	72.51	3.52
5.284031	93.09	10.09	33.63	0.56	1.00	18.70	33.93	32.2%	0.55	64.18	3.43
5.01976	93.04	10.14	32.56	0.52	0.95	17.05	32.85	31.2%	0.52	56.46	3.31
4.755489	92.99	10.19	31.50	0.49	0.90	15.45	31.76	30.1%	0.49	49.32	3.19
4.491219	92.94	10.24	30.44	0.46	0.85	13.90	30.68	29.1%	0.45	42.75	3.08
4.226948	92.89	10.29	29.37	0.42	0.80	12.40	29.60	28.1%	0.42	36.73	2.96
3.962678	92.84	10.34	28.98	0.38	0.75	10.95	29.18	27.7%	0.38	31.26	2.86
3.698407	92.79	10.39	28.58	0.33	0.70	9.51	28.77	27.3%	0.33	26.30	2.77
3.434136	92.74	10.44	28.19	0.29	0.65	8.09	28.35	26.9%	0.29	21.85	2.70
3.169866	92.69	10.49	27.79	0.24	0.60	6.69	27.93	26.5%	0.24	17.89	2.68
2.905595	92.64	10.54	25.88	0.21	0.55	5.35	26.00	24.7%	0.21	14.39	2.69
2.641325	92.59	10.59	18.71	0.23	0.50	4.23	18.79	17.8%	0.23	11.34	2.68
2.377054	92.54	10.64	15.42	0.22	0.45	3.38	15.49	14.7%	0.22	8.71	2.58
2.112783	92.49	10.69	11.14	0.24	0.40	2.71	11.21	10.6%	0.24	6.49	2.39
1.848513	92.44	10.74	10.61	0.20	0.35	2.17	10.66	10.1%	0.20	4.65	2.14
1.584242	92.39	10.79	10.07	0.16	0.30	1.65	10.12	9.6%	0.16	3.16	1.91
1.319971	92.34	10.84	9.54	0.12	0.25	1.16	9.57	9.1%	0.12	2.00	1.72
1.055701	92.29	10.89	9.00	0.08	0.20	0.70	9.03	8.6%	0.08	1.15	1.64
0.79143	92.24	10.94	5.75	0.06	0.15	0.33	5.77	5.5%	0.06	0.56	1.68
0.52716	92.19	10.99	2.50	0.05	0.10	0.12	2.51	2.4%	0.05	0.20	1.61
0.262889	92.14	11.04	1.25	0.02	0.05	0.03	1.26	1.2%	0.02	0.04	1.13

STAGING TABLE - SITE X5

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
5.982391	96.34	7.55	87.03	2.57	4.05	223.51	89.95	100.0%	2.48	2796.94	12.51
4.476024	95.29	8.60	77.50	1.77	3.00	137.48	79.31	88.2%	1.73	772.23	5.62
4.404288	95.24	8.65	77.29	1.73	2.95	133.61	79.05	87.9%	1.69	718.82	5.38
4.332552	95.19	8.70	77.09	1.68	2.90	129.75	78.79	87.6%	1.65	668.31	5.15
4.260816	95.14	8.75	76.89	1.64	2.85	125.90	78.54	87.3%	1.60	620.59	4.93
4.18908	95.09	8.80	76.68	1.59	2.80	122.06	78.28	87.0%	1.56	575.56	4.72
4.117344	95.04	8.85	76.48	1.55	2.75	118.23	78.02	86.7%	1.52	533.10	4.51
4.045608	94.99	8.90	76.28	1.50	2.70	114.41	77.76	86.4%	1.47	493.11	4.31
3.973872	94.94	8.95	76.07	1.45	2.65	110.60	77.50	86.2%	1.43	455.48	4.12
3.902136	94.89	9.00	75.87	1.41	2.60	106.80	77.24	85.9%	1.38	420.12	3.93
3.8304	94.84	9.05	75.67	1.36	2.55	103.02	76.98	85.6%	1.34	386.92	3.76
3.758664	94.79	9.10	75.46	1.32	2.50	99.24	76.72	85.3%	1.29	355.79	3.59
3.686928	94.74	9.15	75.26	1.27	2.45	95.47	76.46	85.0%	1.25	326.64	3.42
3.615192	94.69	9.20	75.05	1.22	2.40	91.71	76.20	84.7%	1.20	299.37	3.26
3.543456	94.64	9.25	74.85	1.18	2.35	87.97	75.94	84.4%	1.16	273.90	3.11
3.47172	94.59	9.30	74.64	1.13	2.30	84.23	75.68	84.1%	1.11	250.14	2.97
3.399984	94.54	9.35	74.44	1.08	2.25	80.50	75.42	83.8%	1.07	228.01	2.83
3.328248	94.49	9.40	74.23	1.03	2.20	76.78	75.16	83.6%	1.02	207.43	2.70
3.256512	94.44	9.45	74.03	0.99	2.15	73.08	74.90	83.3%	0.98	188.31	2.58
3.184776	94.39	9.50	73.82	0.94	2.10	69.38	74.64	83.0%	0.93	170.59	2.46
3.11304	94.34	9.55	73.62	0.89	2.05	65.70	74.38	82.7%	0.88	154.19	2.35
3.041304	94.29	9.60	73.41	0.84	2.00	62.02	74.12	82.4%	0.84	139.04	2.24
2.969568	94.24	9.65	73.21	0.80	1.95	58.36	73.86	82.1%	0.79	125.07	2.14
2.897832	94.19	9.70	73.00	0.75	1.90	54.70	73.61	81.8%	0.74	112.21	2.05
2.826096	94.14	9.75	72.18	0.71	1.85	51.07	72.77	80.9%	0.70	100.40	1.97
2.75436	94.09	9.80	71.37	0.67	1.80	47.48	71.94	80.0%	0.66	89.58	1.89
2.682624	94.04	9.85	70.55	0.62	1.75	43.93	71.10	79.0%	0.62	79.68	1.81
2.610888	93.99	9.90	63.74	0.63	1.70	40.43	64.27	71.4%	0.63	70.65	1.75
2.539152	93.94	9.95	60.67	0.62	1.65	37.32	61.18	68.0%	0.61	62.44	1.67
2.467416	93.89	10.00	54.60	0.63	1.60	34.36	55.09	61.2%	0.62	54.98	1.60
2.39568	93.84	10.05	51.54	0.62	1.55	31.71	52.01	57.8%	0.61	48.24	1.52
2.323944	93.79	10.10	48.47	0.60	1.50	29.20	48.92	54.4%	0.60	42.15	1.44
2.252208	93.74	10.15	46.90	0.57	1.45	26.82	47.33	52.6%	0.57	36.68	1.37
2.180472	93.69	10.20	45.33	0.54	1.40	24.51	45.75	50.9%	0.54	31.77	1.30
2.108736	93.64	10.25	43.77	0.51	1.35	22.29	44.16	49.1%	0.50	27.39	1.23
2.037	93.59	10.30	42.20	0.48	1.30	20.14	42.58	47.3%	0.47	23.49	1.17
1.965264	93.54	10.35	38.14	0.48	1.25	18.13	38.49	42.8%	0.47	20.04	1.11
1.893528	93.49	10.40	31.07	0.53	1.20	16.32	31.41	34.9%	0.52	16.99	1.04
1.821792	93.44	10.45	29.50	0.50	1.15	14.81	29.82	33.2%	0.50	14.31	0.97
1.750056	93.39	10.50	24.93	0.54	1.10	13.37	25.24	28.1%	0.53	11.98	0.90
1.67832	93.34	10.55	24.37	0.50	1.05	12.14	24.65	27.4%	0.49	9.95	0.82
1.606584	93.29	10.60	23.80	0.46	1.00	10.94	24.07	26.8%	0.45	8.19	0.75
1.534848	93.24	10.65	23.23	0.42	0.95	9.76	23.48	26.1%	0.42	6.69	0.69
1.463112	93.19	10.70	22.67	0.38	0.90	8.61	22.89	25.5%	0.38	5.41	0.63
1.391376	93.14	10.75	22.10	0.34	0.85	7.50	22.31	24.8%	0.34	4.33	0.58
1.31964	93.09	10.80	15.53	0.41	0.80	6.40	15.72	17.5%	0.41	3.42	0.53
1.247904	93.04	10.85	14.72	0.38	0.75	5.65	14.89	16.5%	0.38	2.67	0.47
1.176168	92.99	10.90	13.90	0.35	0.70	4.93	14.05	15.6%	0.35	2.05	0.42
1.104432	92.94	10.95	13.08	0.33	0.65	4.26	13.22	14.7%	0.32	1.55	0.36
1.032696	92.89	11.00	12.26	0.30	0.60	3.63	12.38	13.8%	0.29	1.15	0.32
0.96096	92.84	11.05	10.70	0.29	0.55	3.05	10.80	12.0%	0.28	0.84	0.27
0.889224	92.79	11.10	9.13	0.28	0.50	2.56	9.21	10.2%	0.28	0.59	0.23
0.817488	92.74	11.15	8.57	0.25	0.45	2.11	8.63	9.6%	0.24	0.41	0.19
0.745752	92.69	11.20	8.00	0.21	0.40	1.70	8.04	8.9%	0.21	0.27	0.16
0.674016	92.64	11.25	7.12	0.19	0.35	1.32	7.16	8.0%	0.18	0.17	0.13
0.60228	92.59	11.30	6.25	0.16	0.30	0.99	6.28	7.0%	0.16	0.11	0.11
0.530544	92.54	11.35	5.37	0.13	0.25	0.70	5.40	6.0%	0.13	0.06	0.09

STAGING TABLE - SITE X6

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
5.146178	97.30	5.35	84.32	3.77	5.57	318.05	88.98	100.0%	3.57	6685.84	21.02
3.517834	95.68	6.97	81.24	2.27	3.95	184.81	83.74	94.1%	2.21	864.85	4.68
3.467578	95.63	7.02	81.19	2.23	3.90	180.75	83.62	94.0%	2.16	800.47	4.43
3.417322	95.58	7.07	81.14	2.18	3.85	176.69	83.50	93.8%	2.12	740.04	4.19
3.367066	95.53	7.12	81.08	2.13	3.80	172.64	83.38	93.7%	2.07	683.38	3.96
3.316809	95.48	7.17	81.03	2.08	3.75	168.58	83.26	93.6%	2.02	630.30	3.74
3.266553	95.43	7.22	80.98	2.03	3.70	164.53	83.13	93.4%	1.98	580.63	3.53
3.216297	95.38	7.27	80.93	1.98	3.65	160.48	83.01	93.3%	1.93	534.19	3.33
3.16604	95.33	7.32	80.88	1.93	3.60	156.44	82.89	93.2%	1.89	490.82	3.14
3.115784	95.28	7.37	80.82	1.89	3.55	152.40	82.77	93.0%	1.84	450.37	2.96
3.065528	95.23	7.42	80.77	1.84	3.50	148.36	82.65	92.9%	1.80	412.67	2.78
3.015271	95.18	7.47	80.72	1.79	3.45	144.32	82.52	92.7%	1.75	377.57	2.62
2.965015	95.13	7.52	80.58	1.74	3.40	140.29	82.33	92.5%	1.70	344.95	2.46
2.914759	95.08	7.57	80.45	1.69	3.35	136.26	82.14	92.3%	1.66	314.66	2.31
2.864502	95.03	7.62	80.31	1.65	3.30	132.24	81.94	92.1%	1.61	286.57	2.17
2.814246	94.98	7.67	80.18	1.60	3.25	128.23	81.75	91.9%	1.57	260.56	2.03
2.76399	94.93	7.72	80.04	1.55	3.20	124.22	81.56	91.7%	1.52	236.50	1.90
2.713734	94.88	7.77	79.35	1.52	3.15	120.24	80.81	90.8%	1.49	214.28	1.78
2.663477	94.83	7.82	78.51	1.48	3.10	116.29	79.92	89.8%	1.46	193.79	1.67
2.613221	94.78	7.87	77.68	1.45	3.05	112.39	79.04	88.8%	1.42	174.93	1.56
2.562965	94.73	7.92	76.84	1.41	3.00	108.52	78.15	87.8%	1.39	157.59	1.45
2.512708	94.68	7.97	76.01	1.38	2.95	104.70	77.27	86.8%	1.36	141.67	1.35
2.462452	94.63	8.02	75.01	1.35	2.90	100.93	76.22	85.7%	1.32	127.09	1.26
2.412196	94.58	8.07	74.00	1.31	2.85	97.20	75.17	84.5%	1.29	113.75	1.17
2.361939	94.53	8.12	73.00	1.28	2.80	93.53	74.12	83.3%	1.26	101.58	1.09
2.311683	94.48	8.17	71.99	1.25	2.75	89.90	73.06	82.1%	1.23	90.49	1.01
2.261427	94.43	8.22	64.00	1.35	2.70	86.50	65.01	73.1%	1.33	80.40	0.93
2.21117	94.38	8.27	62.45	1.33	2.65	83.34	63.45	71.3%	1.31	71.25	0.85
2.160914	94.33	8.32	60.91	1.32	2.60	80.26	61.88	69.5%	1.30	62.97	0.78
2.110658	94.28	8.37	60.36	1.28	2.55	77.22	61.31	68.9%	1.26	55.48	0.72
2.060402	94.23	8.42	59.82	1.24	2.50	74.22	60.74	68.3%	1.22	48.74	0.66
2.010145	94.18	8.47	59.27	1.20	2.45	71.24	60.17	67.6%	1.18	42.68	0.60
1.959889	94.13	8.52	58.73	1.16	2.40	68.29	59.60	67.0%	1.15	37.25	0.55
1.909633	94.08	8.57	58.18	1.12	2.35	65.37	59.03	66.3%	1.11	32.39	0.50
1.859376	94.03	8.62	57.64	1.08	2.30	62.47	58.46	65.7%	1.07	28.07	0.45
1.80912	93.98	8.67	56.84	1.05	2.25	59.61	57.64	64.8%	1.03	24.22	0.41
1.758864	93.93	8.72	56.05	1.01	2.20	56.79	56.82	63.9%	1.00	20.82	0.37
1.708607	93.88	8.77	55.25	0.98	2.15	54.01	56.00	62.9%	0.96	17.81	0.33
1.658351	93.83	8.82	54.45	0.94	2.10	51.26	55.18	62.0%	0.93	15.17	0.30
1.608095	93.78	8.87	52.91	0.92	2.05	48.58	53.61	60.3%	0.91	12.86	0.26
1.557838	93.73	8.92	51.36	0.90	2.00	45.97	52.04	58.5%	0.88	10.84	0.24
1.507582	93.68	8.97	49.82	0.87	1.95	43.44	50.48	56.7%	0.86	9.09	0.21
1.457326	93.63	9.02	48.27	0.85	1.90	40.99	48.91	55.0%	0.84	7.57	0.18
1.40707	93.58	9.07	47.48	0.81	1.85	38.60	48.09	54.0%	0.80	6.27	0.16
1.356813	93.53	9.12	46.68	0.78	1.80	36.24	47.27	53.1%	0.77	5.16	0.14
1.306557	93.48	9.17	45.89	0.74	1.75	33.93	46.45	52.2%	0.73	4.21	0.12
1.256301	93.43	9.22	42.09	0.75	1.70	31.65	42.63	47.9%	0.74	3.41	0.11
1.206044	93.38	9.27	41.55	0.71	1.65	29.56	42.06	47.3%	0.70	2.74	0.09
1.155788	93.33	9.32	41.00	0.67	1.60	27.50	41.49	46.6%	0.66	2.18	0.08
1.105532	93.28	9.37	40.41	0.63	1.55	25.47	40.88	45.9%	0.62	1.71	0.07
1.055275	93.23	9.42	39.81	0.59	1.50	23.46	40.27	45.3%	0.58	1.34	0.06
1.005019	93.18	9.47	39.22	0.55	1.45	21.48	39.66	44.6%	0.54	1.03	0.05
0.954763	93.13	9.52	32.63	0.60	1.40	19.54	33.06	37.1%	0.59	0.78	0.04
0.904506	93.08	9.57	31.78	0.56	1.35	17.93	32.20	36.2%	0.56	0.58	0.03
0.85425	93.03	9.62	30.94	0.53	1.30	16.36	31.34	35.2%	0.52	0.43	0.03
0.803994	92.98	9.67	30.09	0.49	1.25	14.83	30.48	34.3%	0.49	0.31	0.02
0.753738	92.93	9.72	29.25	0.46	1.20	13.35	29.62	33.3%	0.45	0.22	0.02

STAGING TABLE - SITE X7

		DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
		WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	WET PERIM	RADIUS	FLOW	VELOCITY
		(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
3.657562	97.68	5.13	71.71	4.04	6.57	289.62	75.16	100.0%	3.85	27641.06	95.44
2.544933	96.01	6.80	64.66	2.73	4.90	176.71	67.27	89.5%	2.63	1582.43	8.95
2.511622	95.96	6.85	64.56	2.69	4.85	173.48	67.12	89.3%	2.58	1426.26	8.22
2.478311	95.91	6.90	64.45	2.64	4.80	170.26	66.97	89.1%	2.54	1283.72	7.54
2.444999	95.86	6.95	64.35	2.60	4.75	167.04	66.83	88.9%	2.50	1153.78	6.91
2.411688	95.81	7.00	64.24	2.55	4.70	163.82	66.68	88.7%	2.46	1035.47	6.32
2.378377	95.76	7.05	64.13	2.50	4.65	160.61	66.53	88.5%	2.41	927.90	5.78
2.345066	95.71	7.10	64.03	2.46	4.60	157.41	66.38	88.3%	2.37	830.22	5.27
2.311755	95.66	7.15	63.92	2.41	4.55	154.21	66.23	88.1%	2.33	741.64	4.81
2.278444	95.61	7.20	63.82	2.37	4.50	151.02	66.08	87.9%	2.29	661.42	4.38
2.245133	95.56	7.25	63.71	2.32	4.45	147.83	65.94	87.7%	2.24	588.89	3.98
2.211822	95.51	7.30	63.61	2.27	4.40	144.65	65.79	87.5%	2.20	523.40	3.62
2.17851	95.46	7.35	63.50	2.23	4.35	141.47	65.64	87.3%	2.16	464.37	3.28
2.145199	95.41	7.40	63.33	2.18	4.30	138.30	65.43	87.1%	2.11	411.23	2.97
2.111888	95.36	7.45	63.16	2.14	4.25	135.14	65.23	86.8%	2.07	363.48	2.69
2.078577	95.31	7.50	62.99	2.10	4.20	131.98	65.02	86.5%	2.03	320.65	2.43
2.045266	95.26	7.55	62.82	2.05	4.15	128.84	64.82	86.2%	1.99	282.29	2.19
2.011955	95.21	7.60	62.26	2.02	4.10	125.71	64.22	85.4%	1.96	248.00	1.97
1.978644	95.16	7.65	61.43	2.00	4.05	122.61	63.37	84.3%	1.93	217.41	1.77
1.945333	95.11	7.70	60.60	1.97	4.00	119.56	62.51	83.2%	1.91	190.16	1.59
1.912021	95.06	7.75	59.78	1.95	3.95	116.55	61.66	82.0%	1.89	165.95	1.42
1.87871	95.01	7.80	58.95	1.93	3.90	113.58	60.80	80.9%	1.87	144.47	1.27
1.845399	94.96	7.85	58.12	1.90	3.85	110.66	59.94	79.8%	1.85	125.46	1.13
1.812088	94.91	7.90	57.29	1.88	3.80	107.77	59.09	78.6%	1.82	108.67	1.01
1.778777	94.86	7.95	56.46	1.86	3.75	104.93	58.23	77.5%	1.80	93.88	0.89
1.745466	94.81	8.00	55.62	1.84	3.70	102.13	57.37	76.3%	1.78	80.87	0.79
1.712155	94.76	8.05	54.79	1.81	3.65	99.37	56.51	75.2%	1.76	69.47	0.70
1.678844	94.71	8.10	53.96	1.79	3.60	96.65	55.65	74.0%	1.74	59.50	0.62
1.645532	94.66	8.15	53.13	1.77	3.55	93.97	54.80	72.9%	1.71	50.80	0.54
1.612221	94.61	8.20	52.30	1.75	3.50	91.34	53.94	71.8%	1.69	43.23	0.47
1.57891	94.56	8.25	51.48	1.71	3.45	88.73	53.46	71.1%	1.66	36.87	0.41
1.545599	94.51	8.30	51.39	1.68	3.40	86.15	52.97	70.5%	1.63	31.00	0.36
1.512288	94.46	8.35	50.93	1.64	3.35	83.59	52.49	69.8%	1.59	26.10	0.31
1.478977	94.41	8.40	50.47	1.61	3.30	81.06	52.00	69.2%	1.56	21.90	0.27
1.445666	94.36	8.45	50.02	1.57	3.25	78.55	51.52	68.5%	1.52	18.36	0.23
1.412354	94.31	8.50	49.56	1.53	3.20	76.06	51.04	67.9%	1.49	15.22	0.20
1.379043	94.26	8.55	48.90	1.51	3.15	73.59	50.35	67.0%	1.46	12.61	0.17
1.345732	94.21	8.60	48.23	1.48	3.10	71.17	49.66	66.1%	1.43	10.40	0.15
1.312421	94.16	8.65	47.57	1.45	3.05	68.77	48.97	65.1%	1.40	8.53	0.12
1.27911	94.11	8.70	46.90	1.42	3.00	66.41	48.27	64.2%	1.38	6.97	0.10
1.245799	94.06	8.75	46.24	1.39	2.95	64.08	47.58	63.3%	1.35	5.66	0.09
1.212488	94.01	8.80	45.57	1.36	2.90	61.79	46.89	62.4%	1.32	4.57	0.07
1.179177	93.96	8.85	44.91	1.33	2.85	59.52	46.20	61.5%	1.29	3.67	0.06
1.145865	93.91	8.90	44.24	1.29	2.80	57.29	45.51	60.6%	1.26	2.93	0.05
1.112554	93.86	8.95	42.96	1.28	2.75	55.11	44.20	58.8%	1.25	2.32	0.04
1.079243	93.81	9.00	41.67	1.27	2.70	53.00	42.88	57.1%	1.24	1.82	0.03
1.045932	93.76	9.05	40.38	1.26	2.65	50.95	41.57	55.3%	1.23	1.42	0.03
1.012621	93.71	9.10	39.09	1.25	2.60	48.96	40.25	53.6%	1.22	1.10	0.02
0.97931	93.66	9.15	37.80	1.24	2.55	47.04	38.94	51.8%	1.21	0.85	0.02
0.945999	93.61	9.20	36.51	1.24	2.50	45.18	37.62	50.1%	1.20	0.65	0.01
0.912688	93.56	9.25	35.22	1.23	2.45	43.39	36.31	48.3%	1.20	0.49	0.01
0.879376	93.51	9.30	33.93	1.23	2.40	41.66	34.99	46.6%	1.19	0.36	0.01
0.846065	93.46	9.35	33.26	1.20	2.35	39.98	34.30	45.6%	1.17	0.27	0.01
0.812754	93.41	9.40	32.60	1.18	2.30	38.33	33.61	44.7%	1.14	0.19	0.01
0.779443	93.36	9.45	31.93	1.15	2.25	36.72	32.92	43.8%	1.12	0.14	0.00
0.746132	93.31	9.50	31.27	1.12	2.20	35.14	32.23	42.9%	1.09	0.10	0.00
0.712821	93.26	9.55	28.73	1.17	2.15	33.64	29.67	39.5%	1.13	0.07	0.00

TNC - X #1

R2X - Runs

ELEV (FT)	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT WET PERIM (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
94.57	7.18	79.44	2.92	4.45	232.01	82.11	100.00%	2.83	1277.28	5.51
92.87	8.88	58.17	2.02	2.75	117.23	59.36	72.30%	1.97	508.31	4.34
92.82	8.93	57.99	1.97	2.7	114.32	59.14	72.00%	1.93	488.71	4.27
92.77	8.98	57.82	1.93	2.65	111.43	58.92	71.80%	1.89	469.42	4.21
92.72	9.03	57.65	1.88	2.6	108.54	58.7	71.50%	1.85	450	4.15
92.67	9.08	57.47	1.84	2.55	105.66	58.48	71.20%	1.81	432.16	4.09
92.62	9.13	57.3	1.79	2.5	102.79	58.26	71.00%	1.76	414.3	4.03
92.57	9.18	57.13	1.75	2.45	99.93	58.05	70.70%	1.72	396.44	3.97
92.52	9.23	56.95	1.7	2.4	97.08	57.83	70.40%	1.68	378.58	3.90
92.47	9.28	56.78	1.66	2.35	94.24	57.61	70.20%	1.64	360.72	3.83
92.42	9.33	56.61	1.61	2.3	91.4	57.39	69.90%	1.59	342.86	3.75
92.37	9.38	56.43	1.57	2.25	88.58	57.17	69.60%	1.55	325	3.67
92.32	9.43	56.26	1.52	2.2	85.76	56.95	69.40%	1.51	312.78	3.65
92.27	9.48	56.09	1.48	2.15	82.95	56.73	69.10%	1.46	301.28	3.63
92.22	9.53	55.91	1.43	2.1	80.15	56.51	68.80%	1.42	289.78	3.62
92.17	9.58	55.74	1.39	2.05	77.36	56.29	68.60%	1.37	278.28	3.60
92.12	9.63	55.57	1.34	2	74.58	56.07	68.30%	1.33	266.78	3.58
92.07	9.68	55.39	1.3	1.95	71.8	55.85	68.00%	1.29	255.28	3.56
92.02	9.73	55.22	1.25	1.9	69.04	55.64	67.80%	1.24	243.78	3.53
91.97	9.78	55.05	1.2	1.85	66.28	55.42	67.50%	1.2	232.28	3.50
91.92	9.83	54.87	1.16	1.8	63.53	55.2	67.20%	1.15	220.78	3.48
91.87	9.88	54.7	1.11	1.75	60.79	54.98	67.00%	1.11	209.28	3.44
91.82	9.93	53.73	1.08	1.7	58.08	54.01	65.80%	1.08	197.78	3.41
91.77	9.98	52.77	1.05	1.65	55.42	53.03	64.60%	1.04	186.28	3.36
91.72	10.03	51.8	1.02	1.6	52.8	52.06	63.80%	1.01	174.78	3.31
91.67	10.08	51.55	0.97	1.55	50.22	51.79	63.50%	0.97	162.32	3.23
91.62	10.13	51.3	0.93	1.5	47.65	51.52	63.20%	0.92	149.88	3.15
91.57	10.18	51.05	0.88	1.45	45.09	51.25	62.80%	0.88	137.44	3.05
91.52	10.23	50.8	0.84	1.4	42.54	50.98	62.50%	0.83	125	2.94
91.47	10.28	50.55	0.79	1.35	40.01	50.7	62.20%	0.79	112.56	2.81
91.42	10.33	50.3	0.75	1.3	37.49	50.43	61.90%	0.74	100.12	2.67
91.37	10.38	49.4	0.71	1.25	35	49.53	60.80%	0.71	90.36	2.58
91.32	10.43	48.5	0.67	1.2	32.55	48.62	59.70%	0.67	81.06	2.49
91.27	10.48	47.58	0.63	1.15	30.15	47.7	58.50%	0.63	72.26	2.4
91.22	10.53	46.67	0.6	1.1	27.79	46.78	57.40%	0.59	63.92	2.3
91.17	10.58	45.62	0.56	1.05	25.48	45.73	56.10%	0.56	56.16	2.2
91.12	10.63	44.58	0.52	1	23.23	44.68	54.80%	0.52	48.87	2.1
91.07	10.68	43.54	0.48	0.95	21.03	43.64	53.60%	0.48	42.06	2
91.02	10.73	42.5	0.44	0.9	18.88	42.59	52.30%	0.44	35.71	1.89
90.97	10.78	39.37	0.43	0.85	16.83	39.46	48.40%	0.43	31.03	1.84
90.92	10.83	37.91	0.39	0.8	14.9	38	46.60%	0.39	25.97	1.74
90.87	10.88	34.71	0.38	0.75	13.08	34.78	42.70%	0.38	22.18	1.7
90.82	10.93	29	0.39	0.7	11.43	29.07	35.70%	0.39	19.95	1.75
90.77	10.98	28	0.36	0.65	10	28.07	34.40%	0.36	16.36	1.64
90.72	11.03	27	0.32	0.6	8.63	27.06	33.20%	0.32	13.1	1.52
90.67	11.08	26	0.28	0.55	7.3	26.06	32.00%	0.28	10.17	1.39
90.62	11.13	24.67	0.24	0.5	6.03	24.72	30.30%	0.24	7.67	1.27
90.57	11.18	23.33	0.21	0.45	4.83	23.38	28.70%	0.21	5.5	1.14
90.52	11.23	21.67	0.17	0.4	3.71	21.71	26.60%	0.17	3.72	1
90.47	11.28	20.21	0.13	0.35	2.66	20.25	24.90%	0.13	2.24	0.84
90.42	11.33	16.25	0.1	0.3	1.69	16.29	20.00%	0.1	1.21	0.72
90.37	11.38	10.84	0.09	0.25	1.01	10.86	13.30%	0.09	0.68	0.67
90.32	11.43	5.42	0.11	0.2	0.6	5.43	6.70%	0.11	0.45	0.75
90.27	11.48	4.38	0.08	0.15	0.36	4.39	5.40%	0.08	0.22	0.61
90.22	11.53	3.33	0.05	0.1	0.17	3.34	4.10%	0.05	0.07	0.44
90.17	11.58	1.67	0.03	0.05	0.04	1.67	2.10%	0.02	0.01	0.28
90.12	11.63	0	#DIV/0!	0	0	0	0.00%	#DIV/0!	#DIV/0!	#DIV/0!

TNC - X #2	R2X - Runs									
ELEV (FT)	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT WET PERIM (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
93.65	5.21	96.97	3.16	6.06	306.46	102.53	100.00%	2.99	1683.25	5.49
93.6	7.27	63.24	2.56	4	161.6	66.55	64.90%	2.43	772.57	4.78
93.55	7.32	63.11	2.51	3.95	158.44	66.37	64.70%	2.39	748.97	4.73
93.5	7.37	62.98	2.47	3.9	155.29	66.18	64.50%	2.35	725.66	4.67
93.45	7.42	62.85	2.42	3.85	152.14	65.99	64.40%	2.31	702.65	4.62
93.4	7.47	62.72	2.38	3.8	149	65.8	64.20%	2.26	679.94	4.56
93.35	7.52	62.59	2.33	3.75	145.87	65.62	64.00%	2.22	657.53	4.51
93.3	7.57	62.46	2.29	3.7	142.75	65.43	63.80%	2.18	635.42	4.45
93.25	7.62	62.33	2.24	3.65	139.63	65.24	63.60%	2.14	613.61	4.39
93.2	7.67	62.2	2.19	3.6	136.51	65.05	63.50%	2.1	592.11	4.34
93.15	7.72	62.07	2.15	3.55	133.41	64.87	63.30%	2.06	570.91	4.28
93.1	7.77	61.94	2.1	3.5	130.3	64.68	63.10%	2.01	550.03	4.22
93.05	7.82	61.81	2.06	3.45	127.21	64.49	62.90%	1.97	529.46	4.16
93	7.87	61.68	2.01	3.4	124.12	64.3	62.70%	1.93	509.20	4.10
92.95	7.92	61.55	1.97	3.35	121.04	64.12	62.50%	1.89	489.26	4.04
92.9	7.97	61.42	1.92	3.3	117.97	63.93	62.40%	1.85	469.64	3.98
92.85	8.02	61.29	1.87	3.25	114.9	63.74	62.20%	1.8	450	3.92
92.8	8.07	61.16	1.83	3.2	111.84	63.55	62.00%	1.76	424.88	3.80
92.75	8.12	61.03	1.78	3.15	108.78	63.37	61.80%	1.72	399.88	3.68
92.7	8.17	60.9	1.74	3.1	105.74	63.18	61.60%	1.67	374.88	3.55
92.65	8.22	60.77	1.69	3.05	102.69	62.99	61.40%	1.63	349.88	3.41
92.6	8.27	60.64	1.64	3	99.66	62.8	61.30%	1.59	324.88	3.26
92.55	8.32	60.51	1.6	2.95	96.63	62.62	61.10%	1.54	314.26	3.25
92.5	8.37	60.38	1.55	2.9	93.61	62.43	60.90%	1.5	303.57	3.24
92.45	8.42	60.25	1.5	2.85	90.59	62.24	60.70%	1.46	292.88	3.23
92.4	8.47	60.12	1.46	2.8	87.58	62.05	60.50%	1.41	282.19	3.22
92.35	8.52	59.99	1.41	2.75	84.58	61.86	60.30%	1.37	271.5	3.21
92.3	8.57	59.86	1.36	2.7	81.58	61.68	60.20%	1.32	260.81	3.20
92.25	8.62	59.73	1.32	2.65	78.59	61.49	60.00%	1.28	250.12	3.18
92.2	8.67	59.6	1.27	2.6	75.61	61.3	59.80%	1.23	239.43	3.17
92.15	8.72	59.46	1.22	2.55	72.63	61.11	59.60%	1.19	228.74	3.15
92.1	8.77	59.33	1.17	2.5	69.66	60.92	59.40%	1.14	218.05	3.13
92.05	8.82	59.2	1.13	2.45	66.7	60.74	59.20%	1.1	207.36	3.11
92	8.87	59.07	1.08	2.4	63.74	60.55	59.10%	1.05	196.67	3.09
91.95	8.92	58.94	1.03	2.35	60.79	60.36	58.90%	1.01	185.98	3.06
91.9	8.97	58.81	0.98	2.3	57.85	60.17	58.70%	0.96	175.29	3.03
91.85	9.02	58.68	0.94	2.25	54.91	59.99	58.50%	0.92	155.33	2.83
91.8	9.07	58.56	0.89	2.2	51.98	59.8	58.30%	0.87	135.38	2.60
91.75	9.12	58.43	0.84	2.15	49.06	59.62	58.10%	0.82	115.43	2.35
91.7	9.17	58.3	0.79	2.1	46.09	59.43	58.00%	0.78	95.48	2.07
91.65	9.22	57.52	0.75	2.05	43.2	58.61	57.20%	0.74	86.48	2
91.6	9.27	56.73	0.71	2	40.34	57.8	56.40%	0.7	77.89	1.93
91.55	9.32	56.43	0.66	1.95	37.51	57.47	56.10%	0.65	69.26	1.85
91.5	9.37	56.12	0.62	1.9	34.7	57.14	55.70%	0.61	61.05	1.76
91.45	9.42	55.82	0.57	1.85	31.9	56.82	55.40%	0.56	53.27	1.67
91.4	9.47	55.51	0.52	1.8	29.12	56.48	55.10%	0.52	45.93	1.58
91.35	9.52	53.92	0.49	1.75	26.38	54.86	53.50%	0.48	39.73	1.51
91.3	9.57	45.65	0.52	1.7	23.82	46.55	45.40%	0.51	37.38	1.57
91.25	9.62	42.97	0.5	1.65	21.6	43.84	42.80%	0.49	33.07	1.53
91.2	9.67	40.3	0.48	1.6	19.52	41.14	40.10%	0.47	29.14	1.49
91.15	9.72	37.92	0.46	1.55	17.57	38.72	37.60%	0.45	25.44	1.45
91.1	9.77	33.35	0.47	1.5	15.78	34.12	33.30%	0.46	23.16	1.47
91.05	9.82	32.25	0.44	1.45	14.14	32.98	32.20%	0.43	19.73	1.4
91	9.87	28.14	0.45	1.4	12.56	28.85	28.10%	0.44	17.7	1.41
90.95	9.92	26.79	0.42	1.35	11.19	27.46	26.80%	0.41	15.08	1.35
90.9	9.97	25.4	0.39	1.3	9.88	26.04	25.40%	0.38	12.71	1.29
90.85	10.02	19.78	0.44	1.25	8.75	20.39	19.90%	0.43	12.22	1.4
90.8	10.07	14.56	0.54	1.2	7.82	15.14	14.80%	0.52	12.35	1.58
90.75	10.12	12.35	0.58	1.15	7.15	12.89	12.60%	0.55	11.83	1.66
90.7	10.17	10.14	0.65	1.1	6.59	10.66	10.40%	0.62	11.72	1.78
90.65	10.22	9.93	0.61	1.05	6.08	10.42	10.20%	0.58	10.43	1.71
90.6	10.27	9.71	0.58	1	5.59	10.17	9.90%	0.55	9.21	1.65
90.55	10.32	9.49	0.54	0.95	5.11	9.93	9.70%	0.52	8.06	1.58
90.5	10.37	9.27	0.5	0.9	4.64	9.68	9.40%	0.48	6.98	1.5
90.45	10.42	9.06	0.46	0.85	4.19	9.43	9.20%	0.44	5.97	1.43
90.4	10.47	8.84	0.42	0.8	3.74	9.19	9.00%	0.41	5.04	1.35
90.35	10.52	8.62	0.38	0.75	3.3	8.94	8.70%	0.37	4.17	1.26
90.3	10.57	8.4	0.34	0.7	2.88	8.7	8.50%	0.33	3.37	1.17
90.25	10.62	8.19	0.3	0.65	2.46	8.45	8.20%	0.29	2.65	1.08
90.2	10.67	7.97	0.26	0.6	2.06	8.21	8.00%	0.25	2.01	0.98
90.15	10.72	7.75	0.21	0.55	1.66	7.96	7.80%	0.21	1.44	0.86
90.1	10.77	7.51	0.17	0.5	1.28	7.7	7.50%	0.17	0.95	0.74
90.05	10.82	5.5	0.17	0.45	0.96	5.65	5.50%	0.17	0.72	0.75
90	10.87	3.5	0.21	0.4	0.73	3.62	3.50%	0.2	0.62	0.65
	10.92	3.15	0.18	0.35	0.57	3.24	3.20%	0.17	0.44	0.77

TNC - X #3

R2X RUN

ELEV (FT)	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT WET PERIM (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
	5.84	79.8	2.84	4.45	226.59	81.56	100.00%	2.78	1569.43	6.93
94.03	6.92	66.64	2.21	3.37	147.5	67.86	83.20%	2.17	867.45	5.88
93.98	6.97	66.03	2.18	3.32	144.19	67.23	82.40%	2.14	840.43	5.83
93.93	7.02	65.42	2.15	3.27	140.9	66.59	81.70%	2.12	813.88	5.78
93.88	7.07	64.81	2.12	3.22	137.64	65.96	80.90%	2.09	787.78	5.72
93.83	7.12	64.2	2.09	3.17	134.42	65.32	80.10%	2.06	762.15	5.67
93.78	7.17	63.59	2.06	3.12	131.22	64.69	79.30%	2.03	736.98	5.62
93.73	7.22	62.98	2.03	3.07	128.06	64.06	78.50%	2	712.26	5.56
93.68	7.27	62.37	2	3.02	124.93	63.42	77.80%	1.97	687.99	5.51
93.63	7.32	61.76	1.97	2.97	121.82	62.79	77.00%	1.94	664.18	5.45
93.58	7.37	61.15	1.94	2.92	118.75	62.15	76.20%	1.91	640.81	5.40
93.53	7.42	60.54	1.91	2.87	115.71	61.52	75.40%	1.88	617.89	5.34
93.48	7.47	59.94	1.88	2.82	112.69	60.89	74.70%	1.85	595.41	5.28
93.43	7.52	59.33	1.85	2.77	109.71	60.25	73.90%	1.82	573.38	5.23
93.38	7.57	58.72	1.82	2.72	106.76	59.62	73.10%	1.79	551.78	5.17
93.33	7.62	58.11	1.79	2.67	103.84	58.98	72.30%	1.76	530.62	5.11
93.28	7.67	57.5	1.76	2.62	100.95	58.35	71.50%	1.73	509.90	5.05
93.23	7.72	56.89	1.72	2.57	98.09	57.72	70.80%	1.7	489.61	4.99
93.18	7.77	56.28	1.69	2.52	95.26	57.08	70.00%	1.67	469.74	4.93
93.13	7.82	55.67	1.66	2.47	92.46	56.45	69.20%	1.64	450	4.87
93.08	7.87	55.06	1.63	2.42	89.7	55.81	68.40%	1.61	387.72	4.82
93.03	7.92	54.45	1.6	2.37	86.96	55.18	67.70%	1.58	325.22	3.74
92.98	7.97	53.84	1.56	2.32	84.25	54.54	66.90%	1.54	312.76	3.71
92.93	8.02	53.23	1.53	2.27	81.57	53.91	66.10%	1.51	300.26	3.68
92.88	8.07	52.61	1.5	2.22	78.93	53.27	65.30%	1.48	287.76	3.65
92.83	8.12	52	1.47	2.17	76.31	52.63	64.50%	1.45	275.26	3.61
92.78	8.17	51.39	1.43	2.12	73.73	52	63.80%	1.42	262.76	3.56
92.73	8.22	50.78	1.4	2.07	71.17	51.36	63.00%	1.39	250.26	3.52
92.68	8.27	50.16	1.37	2.02	68.65	50.72	62.20%	1.35	237.76	3.46
92.63	8.32	49.55	1.34	1.97	66.16	50.09	61.40%	1.32	225.26	3.40
92.58	8.37	48.94	1.3	1.92	63.7	49.45	60.60%	1.29	212.76	3.34
92.53	8.42	48.33	1.27	1.87	61.26	48.81	59.90%	1.26	200.26	3.27
92.48	8.47	47.71	1.23	1.82	58.86	48.18	59.10%	1.22	187.76	3.19
92.43	8.52	47.12	1.2	1.77	56.55	47.56	58.30%	1.19	175.26	3.10
92.38	8.57	46.52	1.17	1.72	54.21	46.93	57.50%	1.16	148.34	2.74
92.33	8.62	45.92	1.13	1.67	51.9	46.3	56.80%	1.12	121.41	2.34
92.28	8.69	45.15	1.08	1.6	48.71	45.49	55.80%	1.07	94.48	1.94
92.23	8.74	44.74	1.04	1.55	46.46	45.07	55.30%	1.03	87.88	1.89
92.18	8.79	44.33	1	1.5	44.24	44.65	54.70%	0.99	81.48	1.84
92.13	8.84	43.92	0.96	1.45	42.03	44.23	54.20%	0.95	75.29	1.79
92.08	8.89	43.52	0.92	1.4	39.84	43.81	53.70%	0.91	69.32	1.74
92.03	8.94	43.11	0.87	1.35	37.68	43.39	53.20%	0.87	63.56	1.69
91.98	8.99	42.7	0.83	1.3	35.53	42.97	52.70%	0.83	58.02	1.63
91.93	9.04	42.29	0.79	1.25	33.41	42.54	52.20%	0.79	52.7	1.58
91.88	9.09	41.88	0.75	1.2	31.3	42.12	51.60%	0.74	47.6	1.52
91.83	9.14	41.26	0.71	1.15	29.23	41.48	50.90%	0.7	42.89	1.47
91.78	9.19	40.62	0.67	1.1	27.18	40.84	50.10%	0.67	38.4	1.41
91.73	9.24	39.99	0.63	1.05	25.16	40.19	49.30%	0.63	34.13	1.36
91.68	9.29	39.35	0.59	1	23.18	39.55	48.50%	0.59	30.09	1.3
91.63	9.34	38.72	0.55	0.95	21.23	38.9	47.70%	0.55	26.27	1.24
91.58	9.39	38.09	0.51	0.9	19.31	38.26	46.90%	0.5	22.68	1.17
91.53	9.44	37.45	0.47	0.85	17.42	37.61	46.10%	0.46	19.32	1.11
91.48	9.49	36.82	0.42	0.8	15.56	36.97	45.30%	0.42	16.2	1.04
91.43	9.54	35.7	0.39	0.75	13.75	35.83	43.90%	0.38	13.45	0.98
91.38	9.59	34.56	0.35	0.7	11.99	34.69	42.50%	0.35	10.95	0.91
91.33	9.64	32.45	0.32	0.65	10.32	32.57	39.90%	0.32	8.88	0.86
91.28	9.69	31.62	0.28	0.6	8.72	31.73	38.90%	0.27	6.83	0.78
91.23	9.74	28.87	0.25	0.55	7.2	28.96	35.50%	0.25	5.28	0.73
91.18	9.79	26.07	0.22	0.5	5.83	26.14	32.10%	0.22	3.97	0.68
91.13	9.84	21.02	0.23	0.45	4.75	21.1	25.90%	0.23	3.26	0.69
91.08	9.89	20.02	0.19	0.4	3.72	20.09	24.60%	0.19	2.24	0.6
91.03	9.94	17.07	0.16	0.35	2.79	17.13	21.00%	0.16	1.55	0.55
90.98	9.99	14.07	0.14	0.3	2.02	14.12	17.30%	0.14	1.02	0.51
90.93	10.04	9.72	0.15	0.25	1.47	9.77	12.00%	0.15	0.77	0.52
90.88	10.09	8.85	0.11	0.2	1.01	8.89	10.90%	0.11	0.44	0.43
90.83	10.14	7.04	0.09	0.15	0.61	7.07	8.70%	0.09	0.22	0.36
90.78	10.19	5.21	0.06	0.1	0.3	5.23	6.40%	0.06	0.08	0.28
90.73	10.24	3.37	0.03	0.05	0.09	3.38	4.10%	0.03	0.01	0.16
90.68	10.29	0.07	0	0	0	0.07	0.10%	0	0	0.01

TNC - X #4

ELEV (FT)	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT NET PERIM (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
95.55	7.63	103.21	1.94	3.46	200.67	105.41	100.00%	1.9	1571.76	7.83
94.79	8.39	85.59	1.51	2.7	128.9	87.16	82.70%	1.48	853.27	6.62
94.74	8.44	84.43	1.48	2.65	124.65	85.96	81.50%	1.45	814.38	6.53
94.69	8.49	83.27	1.45	2.6	120.46	84.76	80.40%	1.42	776.49	6.45
94.64	8.54	82.11	1.42	2.55	116.32	83.56	79.30%	1.39	739.58	6.36
94.59	8.59	80.95	1.39	2.5	112.25	82.36	78.10%	1.36	703.64	6.27
94.54	8.64	79.79	1.36	2.45	108.23	81.16	77.00%	1.33	668.66	6.18
94.49	8.69	78.63	1.33	2.4	104.27	79.96	75.90%	1.3	634.65	6.09
94.44	8.74	77.47	1.3	2.35	100.37	78.76	74.70%	1.27	601.59	5.99
94.39	8.79	76.31	1.26	2.3	96.52	77.56	73.60%	1.24	569.47	5.90
94.34	8.84	75.16	1.23	2.25	92.73	76.36	72.40%	1.21	538.29	5.80
94.29	8.89	74	1.2	2.2	89	75.16	71.30%	1.18	508.03	5.71
94.24	8.94	72.84	1.17	2.15	85.33	73.96	70.20%	1.15	478.70	5.61
94.19	8.99	71.68	1.14	2.1	81.72	72.76	69.00%	1.12	450	5.51
94.14	9.04	70.52	1.11	2.05	78.17	71.56	67.90%	1.09	387.5	4.96
94.09	9.09	69.36	1.08	2	74.67	70.36	66.70%	1.06	325	4.35
94.04	9.14	68.2	1.04	1.95	71.23	69.16	65.60%	1.03	313.48	4.40
93.99	9.19	67.04	1.01	1.9	67.85	67.96	64.50%	1	301.94	4.45
93.94	9.24	65.88	0.98	1.85	64.53	66.76	63.30%	0.97	290.4	4.50
93.89	9.29	64.72	0.95	1.8	61.26	65.56	62.20%	0.93	278.86	4.55
93.84	9.34	63.56	0.91	1.75	58.05	64.36	61.10%	0.9	267.32	4.60
93.79	9.39	62.4	0.88	1.7	54.9	63.16	59.90%	0.87	255.78	4.66
93.74	9.44	61.11	0.85	1.65	51.82	61.82	58.60%	0.84	244.24	4.71
93.69	9.49	59.82	0.82	1.6	48.79	60.49	57.40%	0.81	232.7	4.77
93.64	9.54	58.53	0.78	1.55	45.84	59.15	56.10%	0.77	221.16	4.82
93.59	9.59	57.23	0.75	1.5	42.94	57.81	54.80%	0.74	209.62	4.88
93.54	9.64	55.94	0.72	1.45	40.11	56.47	53.60%	0.71	198.08	4.94
93.49	9.69	54.65	0.68	1.4	37.35	55.14	52.30%	0.68	186.54	4.99
93.44	9.74	53.35	0.65	1.35	34.65	53.8	51.00%	0.64	175	5.05
93.39	9.79	52.31	0.61	1.3	32.01	52.73	50.00%	0.61	100.02	3.12
93.34	9.84	48.94	0.6	1.25	29.48	49.34	46.80%	0.6	91.14	3.09
93.29	9.89	47.88	0.57	1.2	27.06	48.26	45.80%	0.56	80.18	2.96
93.24	9.94	44.82	0.55	1.15	24.74	45.18	42.90%	0.55	72.17	2.92
93.19	9.99	39.75	0.57	1.1	22.57	40.09	38.00%	0.56	67.1	2.97
93.14	10.04	38.69	0.53	1.05	20.61	39.01	37.00%	0.53	58.73	2.85
93.09	10.09	33.63	0.56	1	18.7	33.93	32.20%	0.55	54.82	2.93
93.04	10.14	32.56	0.52	0.95	17.05	32.85	31.20%	0.52	48	2.82
92.99	10.19	31.5	0.49	0.9	15.45	31.76	30.10%	0.49	41.64	2.70
92.94	10.24	30.44	0.46	0.85	13.9	30.68	29.10%	0.45	35.74	2.57
92.89	10.29	29.38	0.42	0.8	12.4	29.6	28.10%	0.42	30.28	2.44
92.84	10.34	28.98	0.38	0.75	10.95	29.18	27.70%	0.38	24.81	2.27
92.79	10.39	28.58	0.33	0.7	9.51	28.77	27.30%	0.33	19.81	2.08
92.74	10.44	28.19	0.29	0.65	8.09	28.35	26.90%	0.29	15.28	1.89
92.69	10.49	27.79	0.24	0.6	6.69	27.93	26.50%	0.24	11.24	1.68
92.64	10.54	25.88	0.21	0.55	5.35	26	24.70%	0.21	8.12	1.52
92.59	10.59	18.71	0.23	0.5	4.23	18.79	17.80%	0.23	6.83	1.61
92.54	10.64	15.42	0.22	0.45	3.38	15.49	14.70%	0.22	5.33	1.58
92.49	10.69	11.14	0.24	0.4	2.71	11.21	10.60%	0.24	4.6	1.69
92.44	10.74	10.61	0.2	0.35	2.17	10.66	10.10%	0.2	3.27	1.51
92.39	10.79	10.07	0.16	0.3	1.65	10.12	9.60%	0.16	2.15	1.3
92.34	10.84	9.54	0.12	0.25	1.16	9.57	9.10%	0.12	1.24	1.07
92.29	10.89	9	0.08	0.2	0.7	9.03	8.60%	0.08	0.55	0.79
92.24	10.94	5.75	0.06	0.15	0.33	5.77	5.50%	0.06	0.21	0.65
92.19	10.99	2.5	0.05	0.1	0.12	2.51	2.40%	0.05	0.07	0.59
92.14	11.04	1.25	0.02	0.05	0.03	1.26	1.20%	0.02	0.01	0.37

TNC - X #5

R2X RUNS

ELEV (FT)	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT WET PERIM (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
96.23	7.55	87.03	2.57	4.05	223.51	89.95	100.00%	2.48	1245.82	5.57
95.78	8	82.62	2.24	3.6	185.34	85.08	94.60%	2.18	946.27	5.11
95.73	8.05	82.13	2.21	3.55	181.22	84.54	94.00%	2.14	915.37	5.05
95.68	8.1	81.65	2.17	3.5	177.13	83.99	93.40%	2.11	884.95	5.00
95.63	8.15	81.16	2.13	3.45	173.06	83.45	92.80%	2.07	854.99	4.94
95.58	8.2	80.67	2.1	3.4	169.01	82.91	92.20%	2.04	825.52	4.88
95.53	8.25	80.18	2.06	3.35	164.99	82.37	91.60%	2	796.52	4.83
95.48	8.3	79.69	2.02	3.3	160.99	81.83	91.00%	1.97	767.99	4.77
95.43	8.35	79.2	1.98	3.25	157.02	81.29	90.40%	1.93	739.94	4.71
95.38	8.4	78.71	1.94	3.2	153.07	80.74	89.80%	1.9	712.36	4.65
95.33	8.45	78.22	1.91	3.15	149.15	80.2	89.20%	1.86	685.26	4.59
95.28	8.5	77.9	1.86	3.1	145.25	79.83	88.70%	1.82	657.68	4.53
95.23	8.55	77.7	1.82	3.05	141.36	79.57	88.50%	1.78	629.94	4.46
95.18	8.6	77.5	1.77	3	137.48	79.31	88.20%	1.73	602.69	4.38
95.13	8.65	77.29	1.73	2.95	133.61	79.05	87.90%	1.69	575.94	4.31
95.08	8.7	77.09	1.68	2.9	129.75	78.79	87.60%	1.65	549.67	4.24
95.03	8.75	76.89	1.64	2.85	125.9	78.54	87.30%	1.6	523.91	4.16
94.98	8.8	76.68	1.59	2.8	122.06	78.28	87.00%	1.56	498.64	4.09
94.93	8.85	76.48	1.55	2.75	118.23	78.02	86.70%	1.52	473.89	4.01
94.88	8.9	76.28	1.5	2.7	114.41	77.76	86.40%	1.47	450	3.93
94.83	8.95	76.07	1.45	2.65	110.6	77.5	86.20%	1.43	387.19	3.50
94.78	9	75.87	1.41	2.6	106.8	77.24	85.90%	1.38	324.69	3.04
94.73	9.05	75.67	1.36	2.55	103.02	76.98	85.60%	1.34	312.18	3.03
94.68	9.1	75.46	1.32	2.5	99.24	76.72	85.30%	1.29	299.7	3.02
94.63	9.15	75.26	1.27	2.45	95.47	76.46	85.00%	1.25	287.22	3.01
94.58	9.2	75.05	1.22	2.4	91.71	76.2	84.70%	1.2	274.74	3.00
94.53	9.25	74.85	1.18	2.35	87.97	75.94	84.40%	1.16	262.26	2.98
94.48	9.3	74.64	1.13	2.3	84.23	75.68	84.10%	1.11	249.78	2.97
94.43	9.35	74.44	1.08	2.25	80.5	75.42	83.80%	1.07	237.3	2.95
94.38	9.4	74.23	1.03	2.2	76.78	75.16	83.60%	1.02	224.82	2.93
94.33	9.45	74.03	0.99	2.15	73.08	74.9	83.30%	0.98	212.34	2.91
94.28	9.5	73.82	0.94	2.1	69.38	74.64	83.00%	0.93	199.86	2.88
94.23	9.55	73.62	0.89	2.05	65.7	74.38	82.70%	0.88	187.38	2.85
94.18	9.6	73.41	0.84	2	62.02	74.12	82.40%	0.84	174.9	2.82
94.13	9.65	73.21	0.8	1.95	58.36	73.86	82.10%	0.79	133.1	2.28
94.09	9.69	73.04	0.76	1.91	55.43	73.66	81.9%	0.75	99.77	1.80
94.04	9.74	72.35	0.72	1.86	51.79	72.94	81.1%	0.71	89.69	1.73
93.99	9.79	71.53	0.67	1.81	48.20	72.10	80.2%	0.67	80.16	1.66
93.94	9.84	70.71	0.63	1.76	44.64	71.27	79.2%	0.63	71.10	1.59
93.89	9.89	69.90	0.59	1.71	41.12	70.43	78.3%	0.58	62.50	1.52
93.84	9.94	61.28	0.62	1.66	37.93	61.80	68.7%	0.61	59.59	1.57
93.79	9.99	58.21	0.60	1.61	34.94	58.71	65.3%	0.60	53.78	1.54
93.74	10.04	52.15	0.62	1.56	32.22	52.62	58.5%	0.61	50.56	1.57
93.69	10.09	49.08	0.61	1.51	29.69	49.53	55.1%	0.60	45.93	1.55
93.64	10.14	47.21	0.58	1.46	27.29	47.65	53.0%	0.57	40.95	1.50
93.59	10.19	45.65	0.55	1.41	24.97	46.06	51.2%	0.54	36.12	1.45
93.54	10.24	44.08	0.52	1.36	22.73	44.48	49.4%	0.51	31.60	1.39
93.49	10.29	42.51	0.48	1.31	20.56	42.90	47.7%	0.48	27.40	1.33
93.44	10.34	38.95	0.48	1.26	18.52	39.31	43.7%	0.47	24.39	1.32
93.39	10.39	34.88	0.48	1.21	16.67	35.23	39.2%	0.47	22.03	1.32
93.34	10.44	29.81	0.51	1.16	15.11	30.14	33.5%	0.50	20.74	1.37
93.29	10.49	28.25	0.48	1.11	13.66	28.56	31.7%	0.48	18.17	1.33
93.24	10.54	24.48	0.51	1.06	12.39	24.77	27.5%	0.50	16.98	1.37
93.19	10.59	23.91	0.47	1.01	11.18	24.18	26.9%	0.46	14.54	1.30
93.14	10.64	23.35	0.43	0.96	10.00	23.60	26.2%	0.42	12.27	1.23
93.09	10.69	22.78	0.39	0.91	8.84	23.01	25.6%	0.38	10.17	1.15
93.04	10.74	22.21	0.35	0.86	7.72	22.43	24.9%	0.34	8.25	1.07
92.99	10.79	21.65	0.31	0.81	6.62	21.84	24.3%	0.30	6.50	0.98
92.94	10.84	14.88	0.39	0.76	5.80	15.05	16.7%	0.39	6.68	1.15
92.89	10.89	14.06	0.36	0.71	5.07	14.22	15.8%	0.36	5.55	1.09
92.84	10.94	13.25	0.33	0.66	4.39	13.38	14.9%	0.33	4.54	1.03
92.79	10.99	12.43	0.30	0.61	3.75	12.55	14.0%	0.30	3.65	0.97
92.74	11.04	11.01	0.29	0.56	3.16	11.12	12.4%	0.28	2.97	0.94
92.69	11.09	9.45	0.28	0.51	2.65	9.53	10.6%	0.28	2.45	0.93
92.64	11.14	8.68	0.25	0.46	2.20	8.75	9.7%	0.25	1.91	0.87
92.59	11.19	8.11	0.22	0.41	1.78	8.16	9.1%	0.22	1.40	0.79
92.54	11.24	7.30	0.19	0.36	1.39	7.34	8.2%	0.19	1.00	0.72
92.49	11.29	6.42	0.16	0.31	1.05	6.46	7.2%	0.16	0.68	0.65
92.44	11.34	5.55	0.14	0.26	0.75	5.58	6.2%	0.13	0.43	0.57
92.39	11.39	4.67	0.11	0.21	0.50	4.70	5.2%	0.11	0.24	0.49
92.34	11.44	3.60	0.08	0.16	0.29	3.61	4.0%	0.08	0.12	0.40

TNC - X #6

R2X RUNS

ELEV	DIST TO	TOP	AVG.	MAX.		WETTED	PERCENT	HYDR		AVG.
(FT)	WATER	WIDTH	DEPTH	DEPTH	AREA	PERIM.	NET PERIM	RADIUS	FLOW	VELOCITY
(FT)	(FT)	(FT)	(FT)	(FT)	(SQ FT)	(FT)	(%)	(FT)	(CFS)	(FT/SEC)
97.3	5.35	84.32	3.77	5.57	318.05	88.98	100.00%	3.57	1474.95	4.64
95.92	6.73	81.49	2.51	4.19	204.34	84.33	94.80%	2.42	731.25	3.58
95.87	6.78	81.44	2.46	4.14	200.26	84.21	94.60%	2.38	707.80	3.53
95.82	6.83	81.39	2.41	4.09	196.19	84.08	94.50%	2.33	684.64	3.49
95.77	6.88	81.33	2.36	4.04	192.13	83.96	94.40%	2.29	661.79	3.44
95.72	6.93	81.28	2.31	3.99	188.06	83.84	94.20%	2.24	639.23	3.40
95.67	6.98	81.23	2.27	3.94	184	83.72	94.10%	2.2	616.98	3.35
95.62	7.03	81.18	2.22	3.89	179.94	83.6	94.00%	2.15	595.03	3.31
95.57	7.08	81.13	2.17	3.84	175.88	83.47	93.80%	2.11	573.40	3.26
95.52	7.13	81.07	2.12	3.79	171.83	83.35	93.70%	2.06	552.07	3.21
95.47	7.18	81.02	2.07	3.74	167.77	83.23	93.50%	2.02	531.06	3.17
95.42	7.23	80.97	2.02	3.69	163.72	83.11	93.40%	1.97	510.36	3.12
95.37	7.28	80.92	1.97	3.64	159.68	82.99	93.30%	1.92	489.99	3.07
95.32	7.33	80.87	1.92	3.59	155.63	82.87	93.10%	1.88	469.94	3.02
95.27	7.38	80.81	1.88	3.54	151.59	82.74	93.00%	1.83	450	2.97
95.22	7.43	80.76	1.83	3.49	147.55	82.62	92.90%	1.79	387.5	2.63
95.17	7.48	80.69	1.78	3.44	143.51	82.49	92.70%	1.74	325	2.26
95.12	7.53	80.56	1.73	3.39	139.48	82.29	92.50%	1.69	312.64	2.24
95.07	7.58	80.42	1.68	3.34	135.46	82.1	92.30%	1.65	297.33	2.19
95.02	7.63	80.29	1.64	3.29	131.44	81.9	92.00%	1.6	282.02	2.15
94.97	7.68	80.15	1.59	3.24	127.43	81.71	91.80%	1.56	266.71	2.09
94.92	7.73	80.01	1.54	3.19	123.42	81.52	91.60%	1.51	251.4	2.04
94.87	7.78	79.18	1.51	3.14	119.45	80.63	90.60%	1.48	236.09	1.98
94.82	7.83	78.35	1.47	3.09	115.51	79.75	89.60%	1.45	220.78	1.91
94.77	7.88	77.51	1.44	3.04	111.61	78.86	88.60%	1.42	205.47	1.84
94.72	7.93	76.68	1.41	2.99	107.76	77.98	87.60%	1.38	190.16	1.76
94.68	7.97	76.01	1.38	2.95	104.7	77.27	86.80%	1.36	174.85	1.67
94.63	8.02	75.01	1.35	2.9	100.93	76.22	85.70%	1.32	157.66	1.56
94.58	8.07	74	1.31	2.85	97.2	75.17	84.50%	1.29	140.45	1.44
94.53	8.12	73	1.28	2.8	93.53	74.12	83.30%	1.26	123.24	1.32
94.48	8.17	71.99	1.25	2.75	89.9	73.06	82.10%	1.23	106.03	1.18
94.43	8.22	64	1.35	2.7	86.5	65.01	73.10%	1.33	100.34	1.16
94.38	8.27	62.45	1.33	2.65	83.34	63.45	71.30%	1.31	95.85	1.15
94.33	8.32	60.91	1.32	2.6	80.25	61.88	69.50%	1.3	91.53	1.14
94.28	8.37	60.36	1.28	2.55	77.22	61.31	68.90%	1.26	86.37	1.12
94.23	8.42	59.82	1.24	2.5	74.22	60.74	68.30%	1.22	81.35	1.10
94.18	8.47	59.27	1.2	2.45	71.24	60.17	67.60%	1.18	76.46	1.07
94.13	8.52	58.73	1.16	2.4	68.29	59.6	67.00%	1.15	71.71	1.05
94.08	8.57	58.18	1.12	2.35	65.37	59.03	66.30%	1.11	67.10	1.03
94.03	8.62	57.64	1.08	2.3	62.47	58.46	65.70%	1.07	62.62	1.00
93.98	8.67	56.84	1.05	2.25	59.61	57.64	64.80%	1.03	58.46	0.98
93.93	8.72	56.05	1.01	2.2	56.79	56.82	63.90%	1	54.44	0.96
93.88	8.77	55.25	0.98	2.15	54.01	56	62.90%	0.96	50.55	0.94
93.83	8.82	54.45	0.94	2.1	51.26	55.18	62.00%	0.93	46.80	0.91
93.78	8.87	52.91	0.92	2.05	48.58	53.61	60.30%	0.91	43.62	0.90
93.73	8.92	51.36	0.9	2	45.97	52.04	58.50%	0.88	40.59	0.88
93.68	8.97	49.82	0.87	1.95	43.44	50.48	56.70%	0.86	37.69	0.87
93.63	9.02	48.27	0.85	1.9	40.99	48.91	55.00%	0.84	34.94	0.85
93.58	9.07	47.48	0.81	1.85	38.6	48.09	54.00%	0.8	31.97	0.83
93.53	9.12	46.68	0.78	1.8	36.24	47.27	53.10%	0.77	29.11	0.80
93.48	9.17	45.89	0.74	1.75	33.93	46.45	52.20%	0.73	26.39	0.78
93.43	9.22	42.09	0.75	1.7	31.65	42.63	47.90%	0.74	24.89	0.79
93.38	9.27	41.55	0.71	1.65	29.56	42.06	47.30%	0.7	22.41	0.76
93.33	9.32	41	0.67	1.6	27.5	41.49	46.60%	0.66	20.05	0.73
93.28	9.37	40.41	0.63	1.55	25.46	40.88	45.90%	0.62	17.81	0.70
93.23	9.42	39.81	0.59	1.5	23.46	40.27	45.30%	0.58	15.69	0.67
93.18	9.47	39.22	0.55	1.45	21.48	39.66	44.60%	0.54	13.69	0.64
93.13	9.52	32.63	0.6	1.4	19.54	33.05	37.10%	0.59	13.19	0.68
93.08	9.57	31.78	0.56	1.35	17.93	32.2	36.20%	0.56	11.63	0.65
93.03	9.62	30.94	0.53	1.3	16.36	31.34	35.20%	0.52	10.17	0.62
92.98	9.67	30.09	0.49	1.25	14.83	30.48	34.30%	0.49	8.80	0.59
92.93	9.72	29.25	0.46	1.2	13.35	29.62	33.30%	0.45	7.52	0.56
92.88	9.77	28.41	0.42	1.15	11.91	28.77	32.30%	0.41	6.34	0.53
92.83	9.82	27.56	0.38	1.1	10.51	27.91	31.40%	0.38	5.25	0.50
92.78	9.87	26.72	0.34	1.05	9.15	27.05	30.40%	0.34	4.26	0.47
92.73	9.92	22.88	0.34	1	7.84	23.19	26.10%	0.34	3.65	0.47
92.68	9.97	20.16	0.34	0.95	6.76	20.45	23.00%	0.33	3.10	0.46

TNC - X #7

R2X RUNS

ELEV (FT)	DIST TO WATER (FT)	TOP WIDTH (FT)	AVG. DEPTH (FT)	MAX. DEPTH (FT)	AREA (SQ FT)	WETTED PERIM. (FT)	PERCENT NET PERIM (%)	HYDR RADIUS (FT)	FLOW (CFS)	AVG. VELOCITY (FT/SEC)
	5.13	71.71	4.04	6.57	289.62	75.16	100.00%	3.85	1183.18	4.09
96.26	6.35	65.95	3.12	5.35	206.06	68.87	91.60%	2.99	711.18	3.45
96.21	6.4	65.77	3.08	5.3	202.77	68.66	91.40%	2.95	693.75	3.42
96.16	6.45	65.59	3.04	5.25	199.49	68.45	91.10%	2.91	676.49	3.39
96.11	6.5	65.4	3	5.2	196.21	68.25	90.80%	2.88	659.43	3.36
96.06	6.55	65.22	2.96	5.15	192.95	68.04	90.50%	2.84	642.55	3.33
96.01	6.6	65.08	2.91	5.1	189.69	67.86	90.30%	2.8	625.63	3.30
95.96	6.65	64.88	2.87	5.05	186.44	67.72	90.10%	2.75	608.75	3.27
95.91	6.7	64.87	2.82	5	183.19	67.57	89.90%	2.71	592.05	3.23
95.86	6.75	64.77	2.78	4.95	179.95	67.42	89.70%	2.67	575.54	3.20
95.81	6.8	64.66	2.73	4.9	176.71	67.27	89.50%	2.63	559.21	3.16
95.76	6.85	64.56	2.69	4.85	173.48	67.12	89.30%	2.58	543.08	3.13
95.71	6.9	64.45	2.64	4.8	170.26	66.97	89.10%	2.54	527.13	3.10
95.66	6.95	64.35	2.6	4.75	167.04	66.83	88.90%	2.5	511.38	3.06
95.61	7	64.24	2.55	4.7	163.82	66.68	88.70%	2.46	495.82	3.03
95.56	7.05	64.13	2.5	4.65	160.61	66.53	88.50%	2.41	480.45	2.99
95.51	7.1	64.03	2.46	4.6	157.41	66.38	88.30%	2.37	465.27	2.96
95.46	7.15	63.92	2.41	4.55	154.21	66.23	88.10%	2.33	450	2.92
95.41	7.2	63.82	2.37	4.5	151.02	66.08	87.90%	2.29	434.13	2.78
95.36	7.25	63.71	2.32	4.45	147.83	65.94	87.70%	2.24	397.88	2.62
95.31	7.3	63.61	2.27	4.4	144.65	65.79	87.50%	2.2	356.63	2.47
95.26	7.35	63.5	2.23	4.35	141.47	65.64	87.30%	2.16	325.38	2.3
95.21	7.4	63.33	2.18	4.3	138.3	65.43	87.10%	2.11	308.68	2.23
95.16	7.45	63.15	2.14	4.25	135.14	65.23	86.80%	2.07	291.96	2.16
95.11	7.5	62.99	2.1	4.2	131.98	65.02	86.50%	2.03	275.24	2.09
95.06	7.55	62.82	2.05	4.15	128.84	64.82	86.20%	1.99	258.52	2.01
95.01	7.6	62.26	2.02	4.1	125.71	64.22	85.40%	1.96	241.8	1.92
94.96	7.65	61.43	2	4.05	122.61	63.37	84.30%	1.93	225.08	1.84
94.91	7.7	60.6	1.97	4	119.56	62.51	83.20%	1.91	208.36	1.74
94.86	7.75	59.78	1.95	3.95	116.55	61.66	82.00%	1.89	191.64	1.64
94.81	7.8	58.95	1.93	3.9	113.58	60.8	80.90%	1.87	174.92	1.54
94.76	7.85	58.12	1.9	3.85	110.66	59.94	79.80%	1.85	163.71	1.48
94.71	7.9	57.29	1.88	3.8	107.77	59.09	78.60%	1.82	152.51	1.42
94.66	7.95	56.46	1.86	3.75	104.93	58.23	77.50%	1.8	141.31	1.35
94.61	8	55.62	1.84	3.7	102.13	57.37	76.30%	1.78	130.11	1.27
94.56	8.05	54.79	1.81	3.65	99.37	56.51	75.20%	1.76	118.91	1.20
94.51	8.1	53.96	1.79	3.6	96.65	55.65	74.00%	1.74	107.71	1.11
94.46	8.15	53.13	1.77	3.55	93.97	54.8	72.90%	1.71	96.51	1.03
94.41	8.2	52.3	1.75	3.5	91.33	53.94	71.80%	1.69	85.31	0.93
94.36	8.25	51.84	1.71	3.45	88.73	53.46	71.10%	1.66	81.79	0.92
94.31	8.3	51.39	1.68	3.4	86.15	52.97	70.50%	1.63	78.33	0.91
94.26	8.35	50.93	1.64	3.35	83.59	52.49	69.80%	1.59	74.95	0.9
94.21	8.4	50.47	1.61	3.3	81.06	52	69.20%	1.56	71.64	0.88
94.16	8.45	50.02	1.57	3.25	78.55	51.52	68.60%	1.52	68.41	0.87
94.11	8.5	49.56	1.53	3.2	76.06	51.04	67.90%	1.49	65.24	0.86
94.06	8.55	48.9	1.51	3.15	73.59	50.35	67.00%	1.46	62.32	0.85
94.01	8.6	48.23	1.48	3.1	71.17	49.66	66.10%	1.43	59.48	0.84
93.96	8.65	47.57	1.45	3.05	68.77	48.97	65.20%	1.4	56.71	0.82
93.91	8.7	46.9	1.42	3	66.41	48.27	64.20%	1.38	54.01	0.81
93.86	8.75	46.24	1.39	2.95	64.08	47.58	63.30%	1.35	51.38	0.8
93.81	8.8	45.57	1.36	2.9	61.79	46.89	62.40%	1.32	48.82	0.79
93.76	8.85	44.91	1.33	2.85	59.52	46.2	61.50%	1.29	46.34	0.78
93.71	8.9	44.24	1.29	2.8	57.29	45.51	60.60%	1.26	43.92	0.77
93.66	8.95	42.96	1.28	2.75	55.11	44.2	58.80%	1.25	41.98	0.76
93.61	9	41.67	1.27	2.7	53	42.88	57.10%	1.24	40.13	0.76
93.56	9.05	40.38	1.26	2.65	50.95	41.57	55.30%	1.23	38.36	0.75
93.51	9.1	39.09	1.25	2.6	48.96	40.25	53.60%	1.22	36.68	0.75
93.46	9.15	37.8	1.24	2.55	47.04	38.94	51.80%	1.21	35.08	0.75
93.41	9.2	36.51	1.24	2.5	45.18	37.62	50.10%	1.2	33.56	0.74
93.36	9.25	35.22	1.23	2.45	43.39	36.31	48.30%	1.2	32.12	0.74
93.31	9.3	33.93	1.23	2.4	41.66	34.99	46.60%	1.19	30.77	0.74
93.26	9.35	33.26	1.2	2.35	39.98	34.3	45.60%	1.17	29.11	0.73
93.21	9.4	32.6	1.18	2.3	38.33	33.61	44.70%	1.14	27.51	0.72
93.16	9.45	31.93	1.15	2.25	36.72	32.92	43.80%	1.12	25.97	0.71
93.11	9.5	31.27	1.12	2.2	35.14	32.23	42.90%	1.09	24.47	0.7
93.06	9.55	28.73	1.17	2.15	33.64	29.67	39.50%	1.13	24.05	0.71
93.01	9.6	27.86	1.16	2.1	32.23	28.77	38.30%	1.12	22.85	0.71
92.96	9.65	26.98	1.14	2.05	30.85	27.87	37.10%	1.11	21.71	0.7
92.91	9.7	26.11	1.13	2	29.53	26.97	35.90%	1.09	20.62	0.7
92.86	9.75	25.45	1.11	1.95	28.24	26.28	35.00%	1.07	19.48	0.69
92.81	9.8	24.78	1.09	1.9	26.98	25.59	34.10%	1.05	18.38	0.68
92.76	9.85	24.12	1.07	1.85	25.76	24.9	33.10%	1.03	17.33	0.67
92.71	9.9	23.45	1.05	1.8	24.57	24.21	32.20%	1.02	16.32	0.66
92.66	9.95	22.79	1.03	1.75	23.41	23.52	31.30%	1	15.35	0.66

Surface and Groundwater Interactions Along the
Middle and Lower San Miguel River, CO:
Implications for Plant Water Sources, Plant Water
Status, and the Susceptibility of Riparian Vegetation
to Impacts from Changing River Base Flows

by:

David J. Cooper, Ph.D.
and
Peter A. Conovitz, M.S.

Research Performed for:

Bureau of Land Management
Montrose District Office

June 2001

INTRODUCTION

Among the larger river systems in the southwestern United States, the San Miguel River is one of the few that remain relatively free-flowing and support a nearly continuous belt of riparian vegetation. The San Miguel River has its headwaters high in the Rocky Mountains, but in its lower reaches flows through an arid region with warm and dry summer weather. In early summer high flows saturate floodplain soils, but by late summer when the mountain snowpack has melted and low river flows occur, riparian plants can undergo severe water stress. Cottonwoods, the dominant riparian trees along the San Miguel River, are the North American tree most prone to drought induced xylem cavitation (Tyree et al. 1994), which can lead to leaf, twig, branch and whole tree death in severe circumstances. This is most likely to occur when soils are dry, water tables are at their seasonal low, and evaporative demand is high.

It has been previously determined that cottonwoods along the San Miguel River are under considerable drought stress during the late summer, and are largely dependant upon groundwater for their late summer water supply (Cooper and Arp 1998). To maintain high quality riparian zones along the San Miguel River it is necessary to more fully understand the importance of river flow and river stage for supporting groundwater aquifers under floodplains. It is also important to determine whether water stress in cottonwoods could be exacerbated by reduced base flows.

Previously, Cooper and Arp (1998) worked at three sites along the San Miguel River; The Nature Conservancy's lower San Miguel River preserve near Uruvan, Piñon Bridge, and a site near the U.S.G.S. Placerville stream gauge. During the spring and summer of 2000, we continued this work focusing on narrow-leaf cottonwood-blue

spruce forests at the Placerville site and Fremont cottonwood forests at the Naturita site, emphasizing surface and groundwater relationships at these sites. The goals of this project were to; (1) evaluate the hydrologic connection between the San Miguel River and floodplain groundwater levels, (2) determine whether cottonwood trees are water stressed in the summer of 2000, and (3) determine the sources of water recharging floodplain groundwater and used by riparian plants at different times of the summer.

STUDY AREA

Two of the three reaches of the San Miguel River studied during the 1998 field season (Cooper and Arp 1999) were selected for the present study; the higher elevation Placerville study site and the lower elevation Uruvan study site. No field measurements were made at the Piñon study site during the 2000 field season. The two study sites represent the dominant riparian vegetation types and hydrogeomorphic conditions occurring along that portion of the river corridor.

Placerville. The high elevation study site is called the Placerville site is at 2,240 m elevation, and is located approximately 5 km downstream from the town of Placerville and just above the confluence with Specie Creek (Figure 1). For this season's year, the study area was expanded to include the floodplain on river-left, in addition to the floodplain on river-right used in the past. The study area also includes the colluvial fan located 1.5 km downstream of the primary study site on river-right. The riparian community along this reach is composed primarily of narrowleaf cottonwood, blue spruce, river birch, alder, red osier dogwood (*Swida sericea*), narrow leaf willow (*Salix*

lucida ssp. *lasiandra*), and sandbar willow (*Salix exigua*). The willows are most often found on the lower elevation portions of the floodplain, while blue spruce is more often found at the higher elevations. Narrowleaf cottonwoods are found at all elevations within the floodplain, although tree age generally increases with elevation. Species nomenclature follows Weber and Wittman (1996).

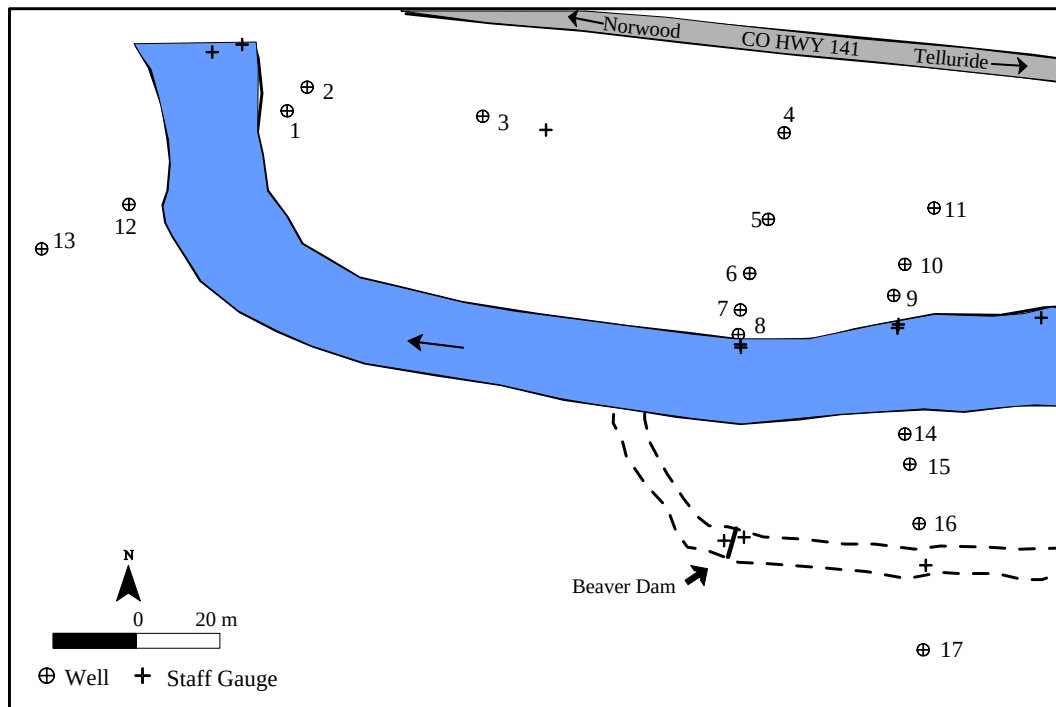


Figure 1. Map of the Placerville study area showing well and staff gauges. Well 18 (not shown) is located approximately 3km west, just north of Hwy. 145.

Narrowleaf cottonwoods along this reach can also be found on colluvial fans and high terraces located well above the floodplain. Within the colluvial fan and high terrace areas, non-riparian plant species including Gambel's Oak (*Quercus gambelii* Nuttall) and Rocky Mountain Juniper (*Sabina scopulorum*).

A number of small channels that were reported to carry flowing water the majority of the summer (Cooper and Arp 1999) were not observed to be active during the 2000 field season, although standing water was usually present except during low river stage. On river-left, a large side channel exists in the lower portion of the floodplain. A beaver dam at the downstream end of this channel influenced the water elevation in this channel through dam construction and deepening.

The floodplain contains a distinct basal cobble layer with bare cobble surfaces exposed at all but the highest flows. At higher elevations, this cobble surface is overlain by a fine-textured soil up to 1 m thickness. Floodplain soils were observed to be heterogeneous in terms of soil thickness and texture and range from coarse sand to sandy loam (Cooper and Arp 1999).

The San Miguel River has a relatively steep gradient through the reach and is mostly confined within the San Miguel Canyon. The streambed is primarily composed of medium sized cobbles and large boulders. Peak flows average $40 \text{ m}^3/\text{s}$ and typically occur in late May to early June and closely corresponds with peak snowmelt in the surrounding San Juan Mountains. Streamflow decreases throughout July and baseflow is usually reached by mid-August and averages less than $10 \text{ m}^3/\text{s}$ (Cooper and Arp 1999). Monsoonal precipitation events can cause higher flows in August, but these typically do not exceed the late spring/early summer peak (Fleener 1997). Some water diversions do occur upstream of the reach but do not remove a large proportion of the water during the growing season.

Uruvan. The Uruvan study area occurs at 1,585 m elevation and is located 5 km upstream from the historic uranium mining community (Figure 2). The study area

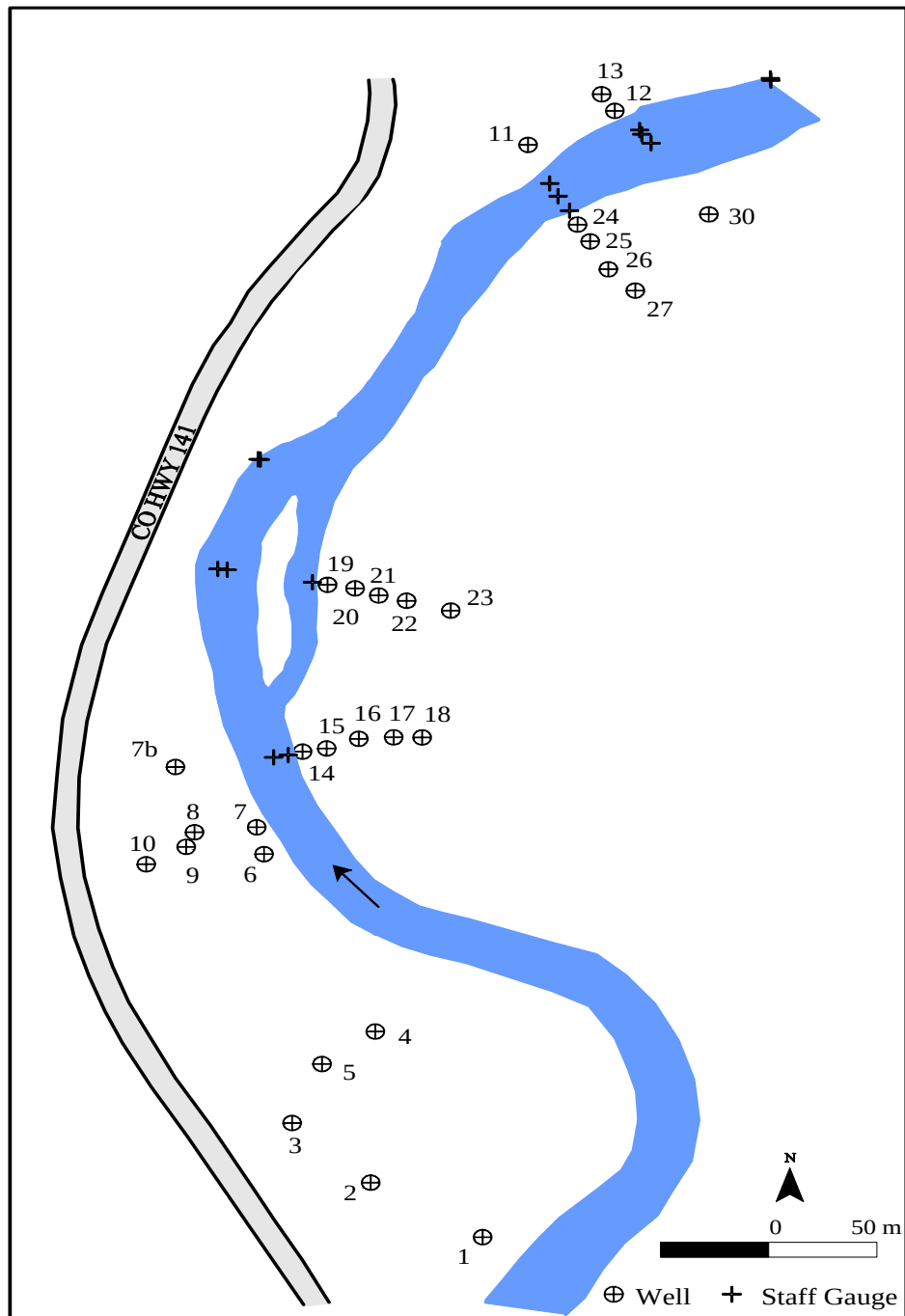


Figure 2. Map of the Uruvan study area showing well and staff gauges.

Was expanded from the 1998 study reach to include the floodplain on river-right. The tree species Fremont cottonwood, and to a lesser extent narrowleaf cottonwood, and hybrid cottonwood (*Populus x acuminata*) are most abundant. Other dominant riparian species include skunk brush (*Rhus trilobata*), New Mexican privet (*Forestiera pubescens*) and willows.

Willows and the reed grass (*Phragmites australis*) dominate the lowest elevation and most frequently flooded portion of the floodplain. Abundant cottonwood saplings are also present. Mature narrowleaf cottonwoods occur only on the mid-elevation portion of the floodplain while Fremont cottonwoods are found at both middle and high floodplain elevations. Some dryland species occur on the high elevation portions of the floodplain including big sagebrush (*Seriphidium tridentatum*) and rabbit brush (*Chrysothamnus nauseosus*) indicating that these areas rarely flood.

On both sides of the river, the floodplain gently slopes upwards towards the canyon sides although vertical, undercut stream banks are present in many locations. Also on both sides of the river, several intermittent tributaries from the canyon sides have formed alluvial fans onto the upper portions of the floodplain. Small hillslope tributaries on river-left generate runoff following one large precipitation event and deposited a sediment layer up to 15 cm thick on the fan. As at the Placerville site, bare exposed cobble surfaces are exposed in many places along the reach except during the highest flows. At higher elevations this cobble surface is overlain by sands and loam-textured soil up to 1 m thick. The effects of past land use activities can be observed on the river-left floodplain, exhibited by areas excavated by heavy machinery and what appears to be the construction of an artificial berm along a short portion of the reach. The river-right side,

on the opposite side from the highway, does not appear modified by similar anthropogenic activities.

The San Miguel River through this study reach has a moderate gradient with a bed primarily composed of cobbles and to a lesser extent sand. Peak flows generally occur in mid- to late May, and average $67 \text{ m}^3/\text{s}$. However, the Dry Creek watershed drains into this section of the San Miguel River and annual peak stream flows frequently occur as a result of short duration monsoonal precipitation events in August (Fleener 1997). In the absence of precipitation driven events, baseflow is reached by mid-August and averages approximately $6 \text{ m}^3/\text{s}$. A relatively large diversion located upstream of the reach, the C.C. ditch, can divert up to $4.1 \text{ m}^3/\text{s}$ during the growing season. This can account for a large proportion of streamflow in July and August.

METHODS

Water Level Measurements. Groundwater and river stage elevations were measured throughout the summer to further establish the relationship between floodplain groundwater levels and river stage. Water levels were measured from late April through early September 2000.

At the two sites, a large number of groundwater wells were installed to augment the well network established by Cooper and Arp in 1998. We also expanded the study area to include both sides of the river at both study sites, and installed wells throughout the area to gain a more detailed understanding of stream-groundwater interactions. At the Placerville site, 12 wells were installed in addition to the 5 established in 1998 (Figure 1). At the Uruvan site, 17 wells were installed in addition to the 10 established in 1998

(Figure 2). The placement of the new wells was such that several transects were established perpendicular to, and extending away from the river in order to develop profiles of water table elevation relative to the river stage. For locations with shallow water tables, wells made from slotted 3.2 cm diameter PVC pipe were installed with a 10 cm diameter auger. In higher elevation areas or areas with coarse textured soil, steel well points were driven into the ground with a fence-post installer. All well casings were capped at the bottom. Water levels were obtained weekly and measured as the depth from the native soil surface to the water table with an electronic tape.

Staff gauges were installed along each monitoring well transect to measure river stage. The staff gauges were composed of steel rebar driven into the channel bed with a hammer. River stage elevation was measured from the top of the rebar to the water surface with a measuring tape. Additional staff gauges were installed in some of the side channels at the Placerville site (Figure 1). River stage was measured in conjunction with groundwater measurements. Due to a decrease in the wetted perimeter of the river with decreasing streamflow, up to three staff gauges were needed at several locations to obtain a continuous weekly record of river stage. All staff gauges and monitoring wells were surveyed with either an auto-level, total station, or GPS unit to obtain relative groundwater and river stage elevations.

Cottonwood Water Source Analysis. The water source utilized by cottonwood was assessed at both study sites in early and late summer using stable hydrogen isotope analysis (δD). Water was extracted from cottonwood twigs, soil at 2 depths (0-20 and 20-70 cm depth), ground water, and river water. Samples were collected following peak flow

(mid-June) and again during lower flows in mid- to late August. Isotope samples were collected at low, middle, and high elevation locations within the floodplain. At Placerville, the low, middle and high elevation sites were located adjacent to wells 3, 4, 18 (colluvial fan site), respectively. At Uruvan, the low, middle and high elevation sites were located adjacent to wells 1, 2, and 3, respectively. At each location, three trees were sampled by collecting three different branches using a tree-trimmer. Wood samples were either placed in a polyethylene sampling bottle or triple bagged in plastic zip-seal sample bags. Also at each location, soil samples were also taken at two depths (0-20 cm and 20-70 cm) at two separate but adjacent locations. The soil samples were triple bagged in plastic zip-seal sample bags. Ground water monitoring wells at each location were purged three times and one water sample was collected in a 30 ml scintillation vial. River samples were collected in 60 ml polyethylene bottles. All sample bottles were further sealed with plastic tape and refrigerated until shipment for analysis.

Water was extracted from soils and xylem using cryogenic distillation methods (Ehleringer and Osmond, 1989). Analyses were performed by Mountain Mass Spectrometry in Evergreen, Colorado.

Cottonwood Water Status Characterization. Cottonwood twig xylem water potential was measured during both pre-dawn (0200 - 0600 h) and mid-day (1300 - 1600 h) time periods using a Scholander-type pressure bomb. Water status measurements were made following the peak flow period in mid-June and again during low-flows in mid- to late August. At each study area, measurements were taken from the same three trees at the

low, middle, and high elevation sites, where the samples for stable isotopes were collected.

RESULTS

Hydrology - Placerville. The hydrograph for the San Miguel River near Placerville during the spring and summer of 2000 exhibited a typical snowmelt dominated pattern (Figure 3). The onset of spring snowmelt caused the river to rise in early April and the peak flow of $30.3 \text{ m}^3/\text{s}$ occurred on 29-30 May. Following the peak, streamflow declined rapidly in June, and more slowly in July and August. The lowest daily flow of $2.3 \text{ m}^3/\text{s}$ occurred on 13 August. Monsoonal rains caused streamflow to increase in mid to late August, but the increase in discharge during this period was not substantial compared with previous years (Fleener 1997).

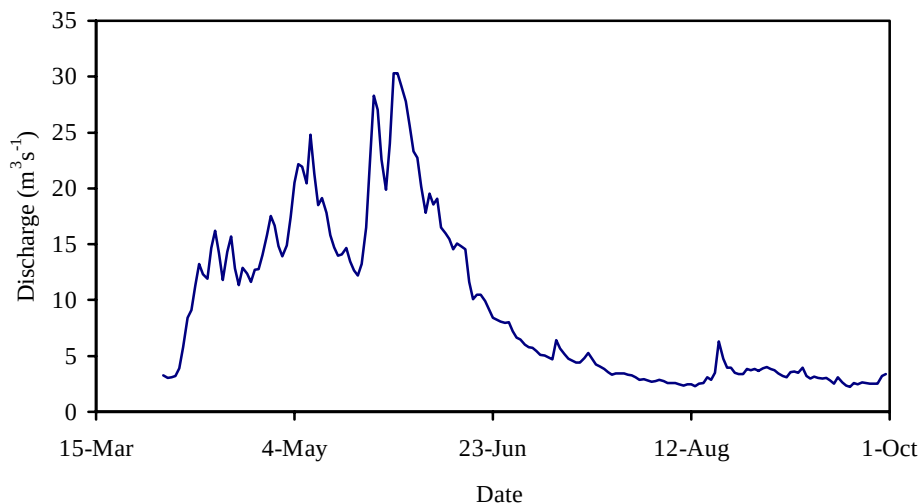


Figure 3. Mean daily discharge for the San Miguel River near Placerville from 1 April 2000 through 30 September 2000.

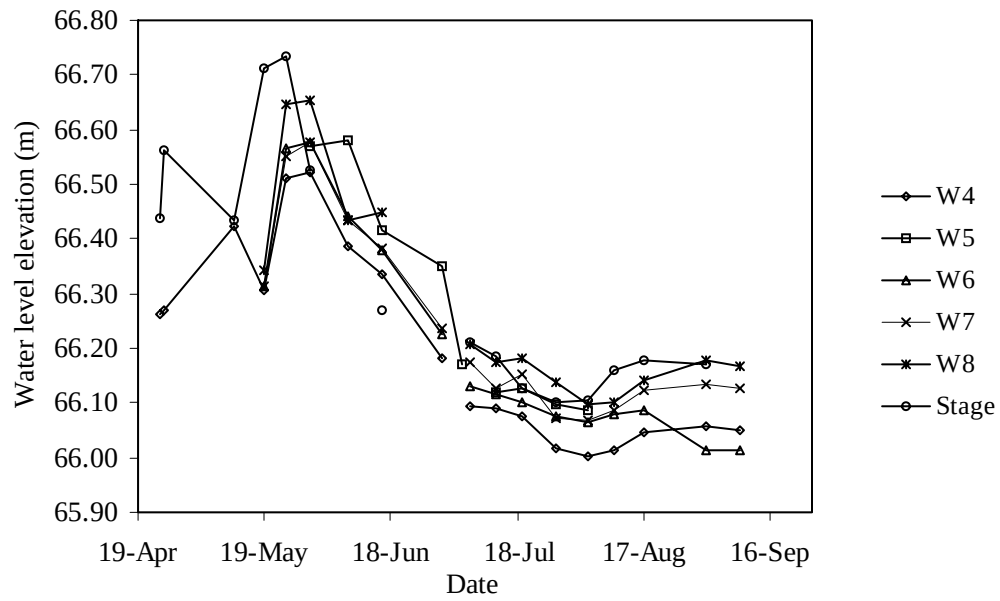
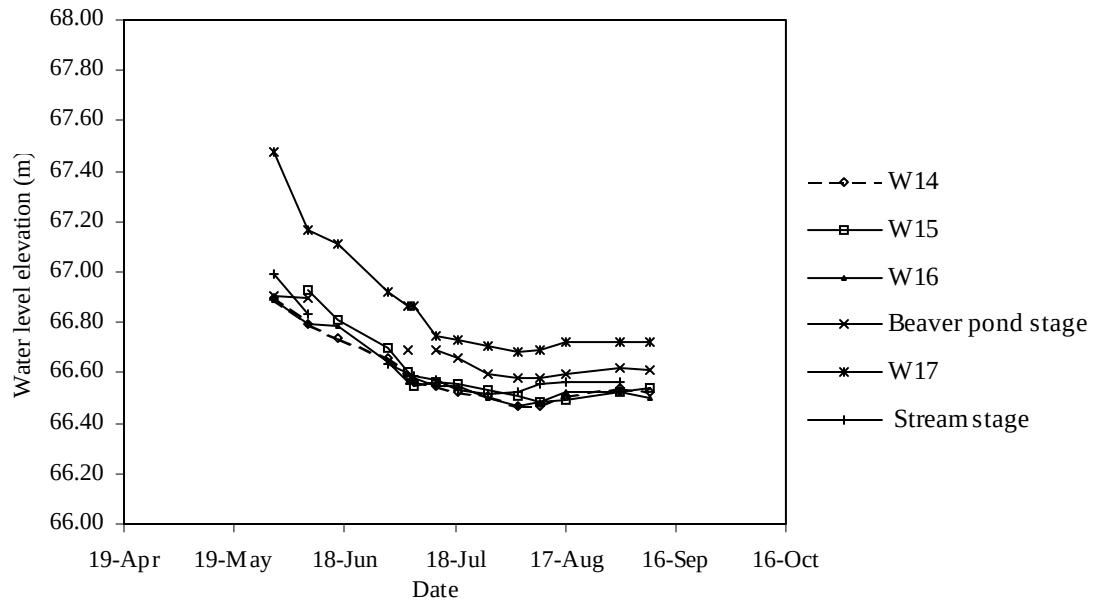


Figure 4. Groundwater and San Miguel River stage elevations at the Placerville study site.

Groundwater levels in all wells at the Placerville site were closely related to changes in river stage (Figure 4). Peak groundwater levels occurred during peak streamflow, and the lowest groundwater levels were recorded during low-flow in the San Miguel River. Over the course of the summer, groundwater levels decreased between 50 and 70 cm, while river stage dropped an average of 65 cm, as measured at our staff gauges.

There was an strong correlation between floodplain groundwater levels and river stage at all well locations (Table 1). For wells 1-17 at the Placerville site, the mean correlation coefficient was 0.99. These correlations are similar to those calculated for the more limited 1998 data set, further suggesting the close coupling between surface and groundwater along the San Miguel riparian corridor.

Table 1. Correlation coefficients for groundwater levels and river stage at Placerville for 1998 and 2000. “-“ indicates that no data was available.

Well #	1998	2000
	R	R
1	1.00	0.99
2	0.96	0.99
3	0.99	0.99
4	0.99	1.00
5	-	1.00
6	-	0.98
7	-	0.99
8	-	1.00
9	-	1.00
10	-	0.99
11	-	0.98
12	-	0.99
13	-	0.99
14	-	0.98
15	-	1.00
16	-	0.99
17	-	0.99

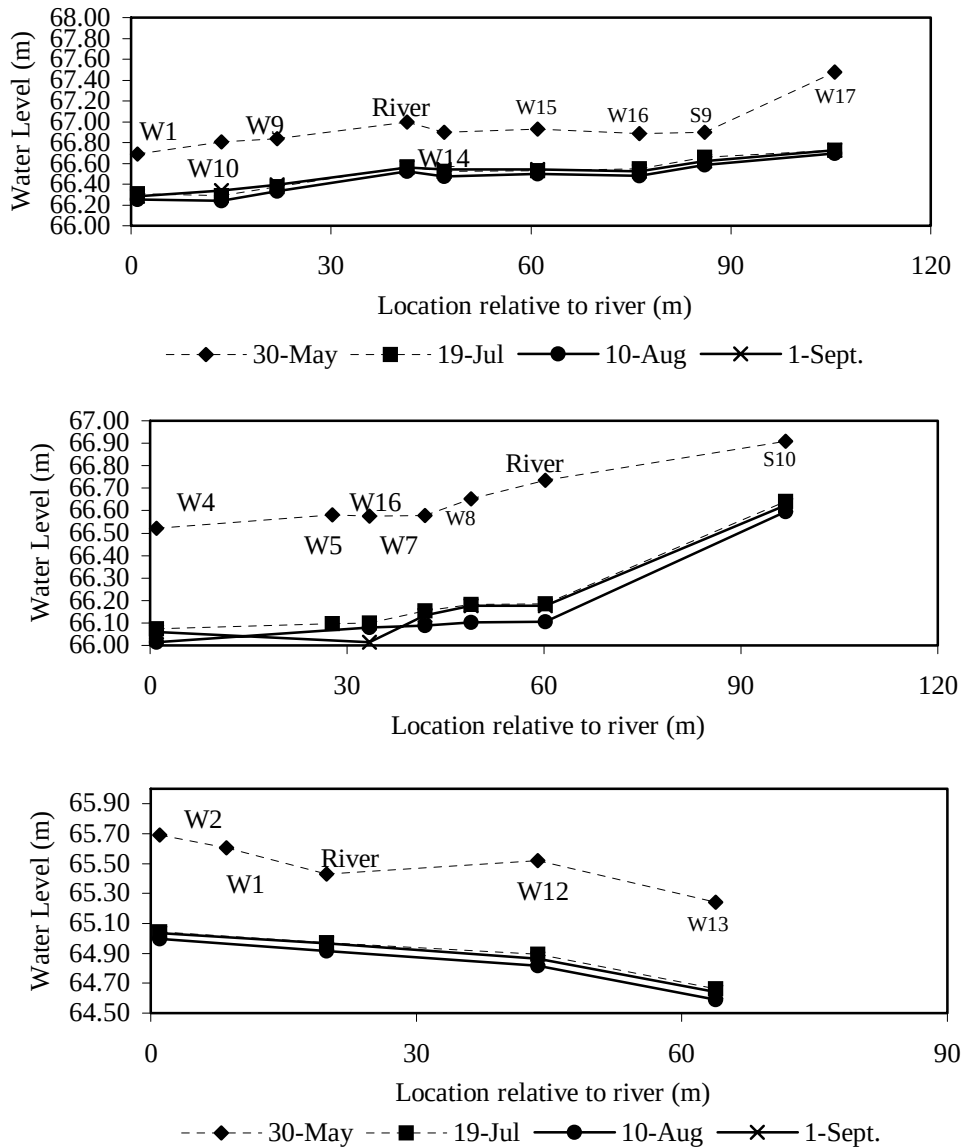
Changes in ground water levels relative to changes in stream stage were relatively constant throughout the summer (Figure 5). For example, on 30 May, the difference in elevation between river stage and the groundwater table at wells 9 and 11 was 16 cm and 31 cm, respectively. By August 10, after a drop in river stage of 45 cm, the difference in elevation between river stage and the groundwater table at wells 9 and 11 was 20 cm and 28 cm, respectively. This difference between river stage and ground water levels was consistent through the summer, with the exception of well 17. On May 30, the groundwater in well 17 was 147 cm above the river elevation. By August 10, the groundwater elevation in well 17 was only 16 cm above the river.

Seasonal changes in groundwater elevations were similar between 1998 and 2000 (Figure 6). For both years the highest groundwater elevations occurred in late May, coinciding with peak streamflow. While peak groundwater elevations were nearly identical in 1998 and 2000, groundwater levels during the summer of 2000 dropped below what was observed in 1998 and all of the wells installed during the 1998 season went dry with the exception of well 4. Well 4 data indicates that for both years there was a small increase in groundwater level in August, presumably in response in increased streamflow driven by monsoonal precipitation.

Groundwater profiles indicate that an active exchange of water exists between the river and the adjacent alluvial aquifer. The most upstream transect suggests that the river is contributing water to the aquifer immediately adjacent to the channel but is also gaining water from hillslope sources (Figures 5,7,8,9). During all measurement periods the river elevation is higher than the groundwater in wells 9-11 and 14-16. The ground water in well 17 however, was consistently above the river elevation suggesting that

hillslope groundwater sources are contributing to streamflow in this location. A beaver pond has created a localized groundwater mound, which is in turn fed by hillslope sources in the area of well 17.

Figure 5. Groundwater elevation profiles relative to San Miguel River stage at Placerville.



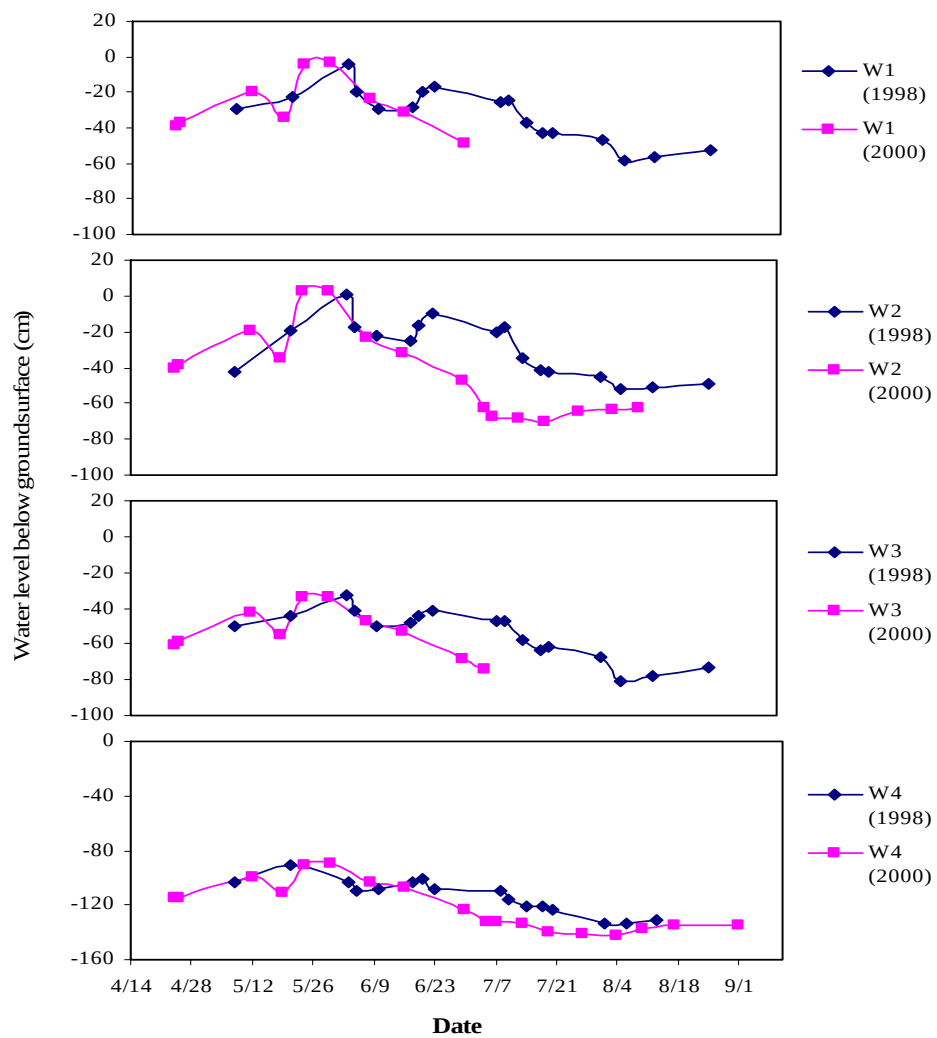


Figure 6. Comparisons of groundwater levels between 1998 and 2000 field seasons at Placerville.

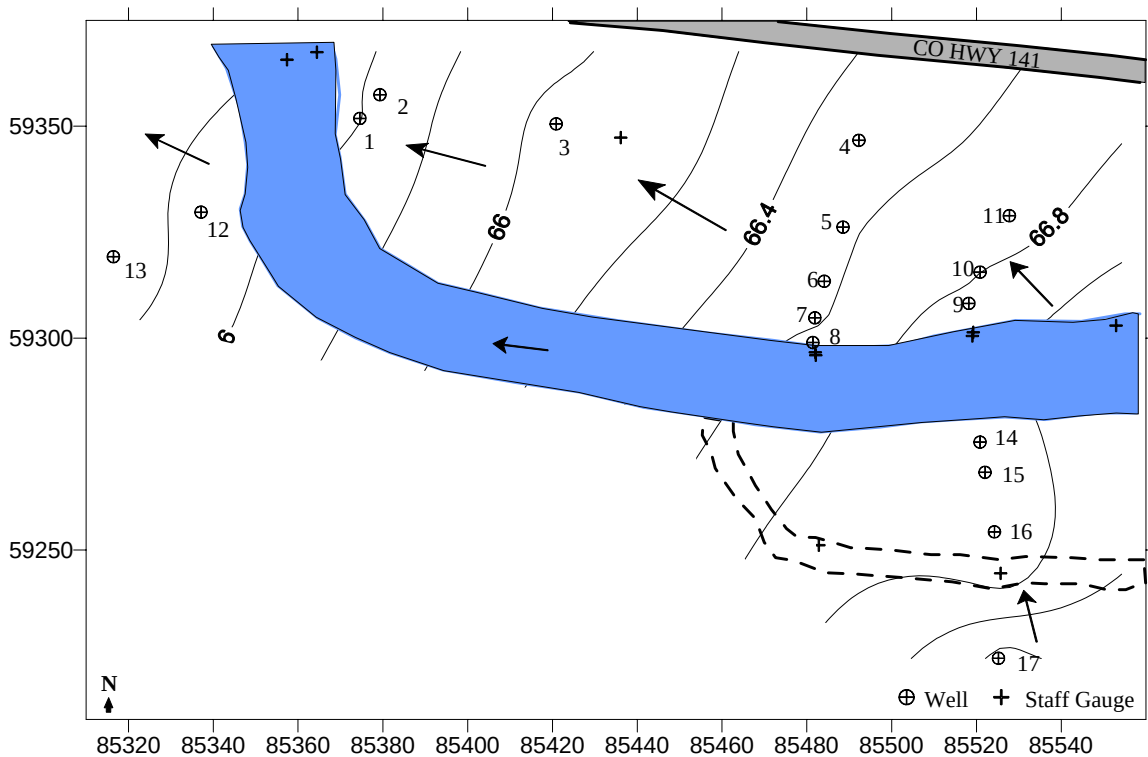


Figure 7. Water table contours for the Placerville study site on 31 May 2000. Map scale and contour elevations are in meters.

Similarly, groundwater profiles along the middle transect in the study reach suggest some multi-directional exchange between the river and adjacent aquifer (Figure 5). Throughout the entire summer, the river appears to lose water to the floodplain aquifer on the north side of the channel while localized rise in the groundwater table generated by the beaver pond is contributing water towards the river. Groundwater profiles along the downstream transect suggest that groundwater is moving back into the river where the channel bends to the north (Figures 5,7,8,9). For most of the summer, the river appears to be contributing water to the aquifer on river-left. During high flow in May, the elevation of the water table at well 12 is higher than the water table elevations in both the river and

in well 13. Specie Creek, which drains into the San Miguel just downstream of wells 12 and 13, may be influencing the groundwater hydrology in this area. Streamflow in Specie Creek may be generating a localized groundwater mound, which may raise water table elevations in the vicinity of well 12.

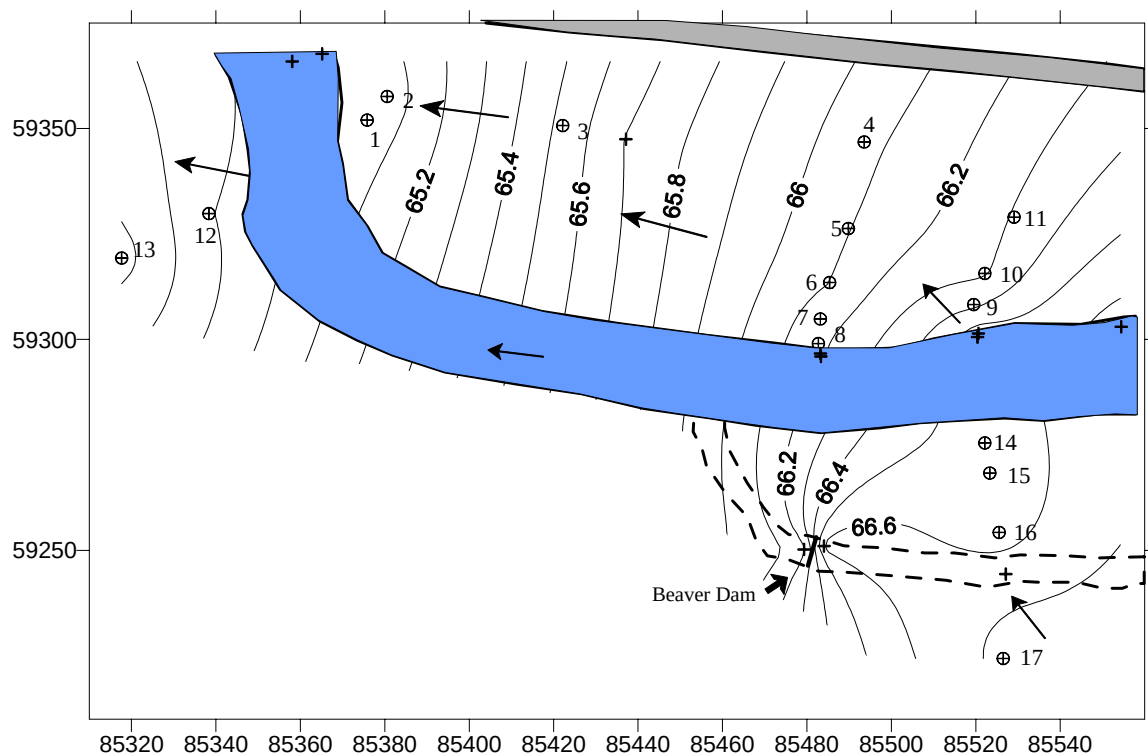


Figure 8. Water table contours for the Placerville study site on 19 July 2000. Map scale and contour elevations are in meters.

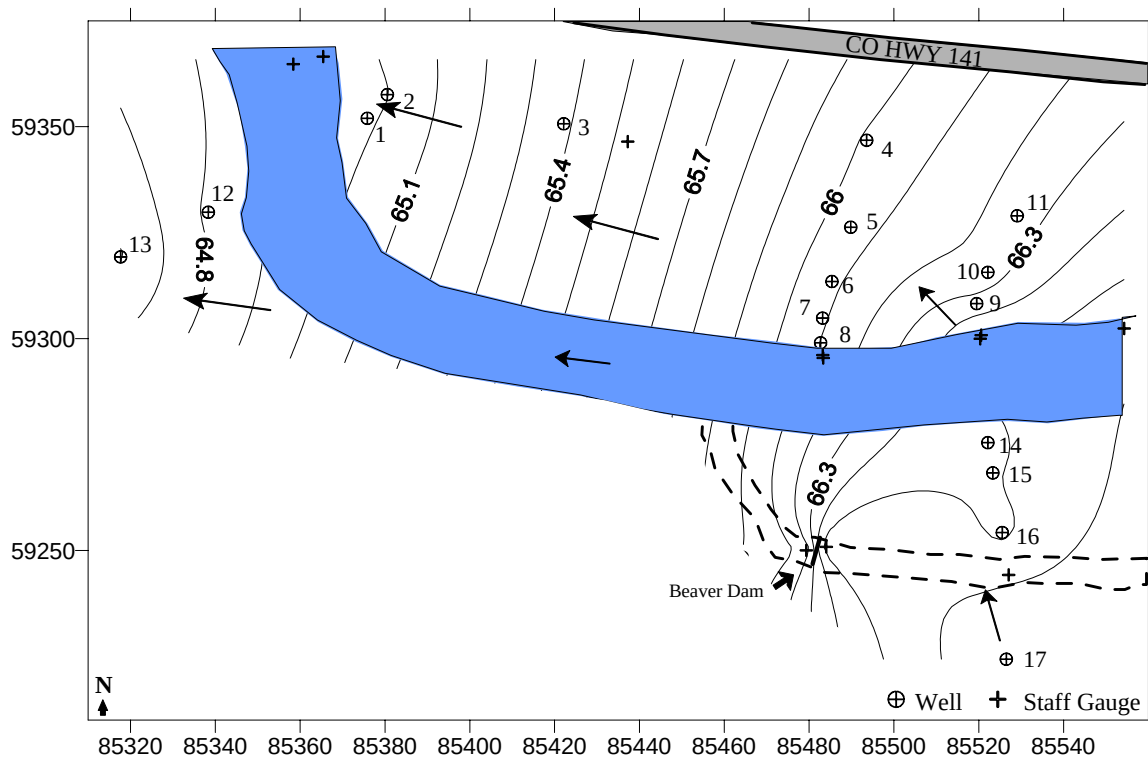


Figure 9. Water table map for the Placerville study site on 11 August 2000. Map scale and contour elevations are in meters.

Hydrology - Uruvan. The hydrograph for the San Miguel River near Uruvan also followed a typical snowmelt pattern during the spring and summer (Figure 10). Spring snowmelt caused streamflow to increase in early April and the mean daily peak flow of $46.2 \text{ m}^3/\text{s}$ occurred on 9 May. Streamflow declined after mid-June and the mean daily low flow of $0.4 \text{ m}^3/\text{s}$ occurred on 12 August. Streamflow increased only slightly in late August due to light monsoon rains in the region.

Changes in groundwater elevations were closely tied to changes in river stage throughout the summer (Figure 11). Absolute changes in both groundwater and river stage were larger than those measured in Placerville. Changes in groundwater elevation ranged from 57 cm to 119 cm. For all wells, the mean change in groundwater elevation was 72 cm between late May and mid-August. For the same period, the mean change in river stage was 81 cm.

Similar to the Placerville study site, there was a strong correlation between river floodplain groundwater levels and river stage at all well locations in Uruvan (Table 2). For wells 1-29 at the Uruvan site, the mean correlation coefficient between stage and groundwater elevation was 0.96 and correlation coefficients for the individual wells ranged from 0.85 - 1.0. These correlations are similar to those calculated for the 1998 data set where the mean correlation coefficient for wells 1-12 was 0.92 and individual values ranged from 0.82 - 0.98. This further suggests the close relationship between floodplain groundwater and river stage at the Uruvan site.

Similar to the Placerville study site, the magnitude of groundwater elevation change was similar to the magnitude of stream stage change throughout the season. On 25 May, the difference in elevation between stream stage and the groundwater surface at

Table 2. Correlation coefficients for groundwater levels and river stage at Uravan for 1998 and 2000. “-“ indicates that no data was available.

Well #	<u>1998</u>	<u>2000</u>
	R	R
1	0.96	1.00
2	0.93	0.92
3	0.82	0.90
4	0.89	0.89
5	0.87	0.90
6	0.98	0.99
7	0.97	1.00
8	0.92	0.98
9	0.87	0.98
10	0.90	0.85
11	0.97	0.97
12	0.96	1.00
13	-	0.93
14	-	0.99
15	-	1.00
16	-	0.99
17	-	0.98
18	-	0.96
19	-	0.98
20	-	0.98
21	-	0.96
22	-	0.96
23	-	0.94
24	-	0.96
25	-	0.99
26	-	0.99
27	-	0.94
28	-	0.98
29	-	0.98
30	-	

wells 15 and 17 was 22 and 42 cm, respectively. By 11 August, despite considerable drop in streamflow, the relative differences in elevation between stream stage and the groundwater elevation at these two wells remained nearly identical, at 23 cm and 40 cm, respectively. This relationship was consistent for most wells (Figures 11, 12).

Seasonal changes in groundwater elevations were similar between 1998 and 2000 (Figure 13). For both years the highest groundwater elevations occurred in late May, coinciding with peak streamflow. Peak groundwater elevations were slightly higher at Uravan in 1998 as compared with 2000 and remained consistently higher throughout the summer. During both years, floodplain groundwater elevations were highest in mid-May although groundwater levels declines more abruptly following the peak in 2000 as compared with 1998.

Profiles of groundwater surface elevations relative to stage along transects perpendicular to the river suggest that water is moving from the river into the adjacent aquifer throughout the reach in all seasons. The river elevation was consistently higher than the water table elevation in wells along the most upstream transect (Figure 12).

This pattern is also observed at the middle and downstream transects (Figures 12-15). Groundwater contour maps also show that along the reach, water is generally moving from the river into the adjacent aquifer during both late spring and late summer. At some locations, the well data suggest that groundwater is also moving back to the river from the floodplain aquifer (Figures 12-15), particularly on inside meander bends.

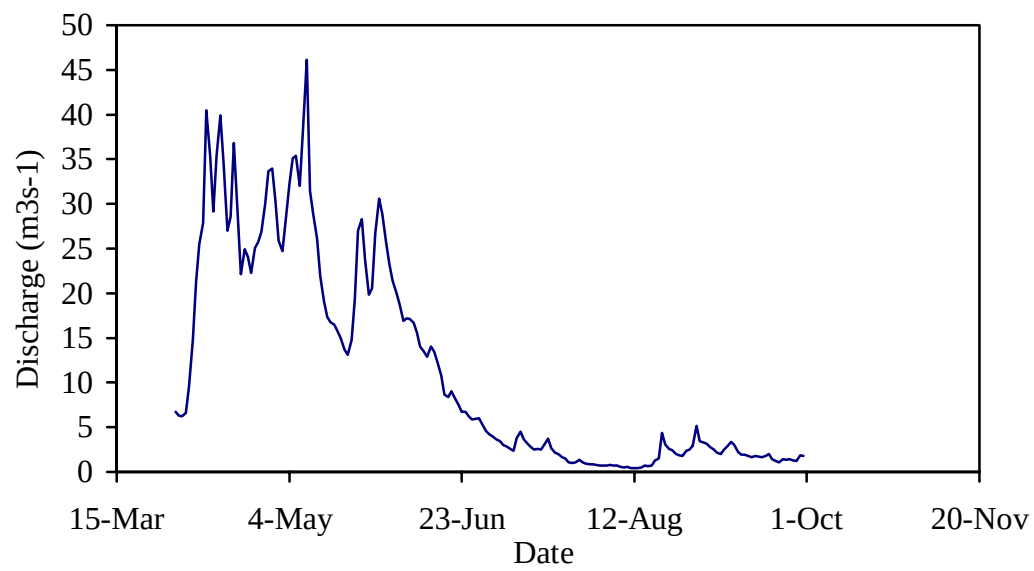


Figure 10. Mean daily discharge in m³/s for the San Miguel River near Uruvan between 1 April 2000 and 30 September 2000.

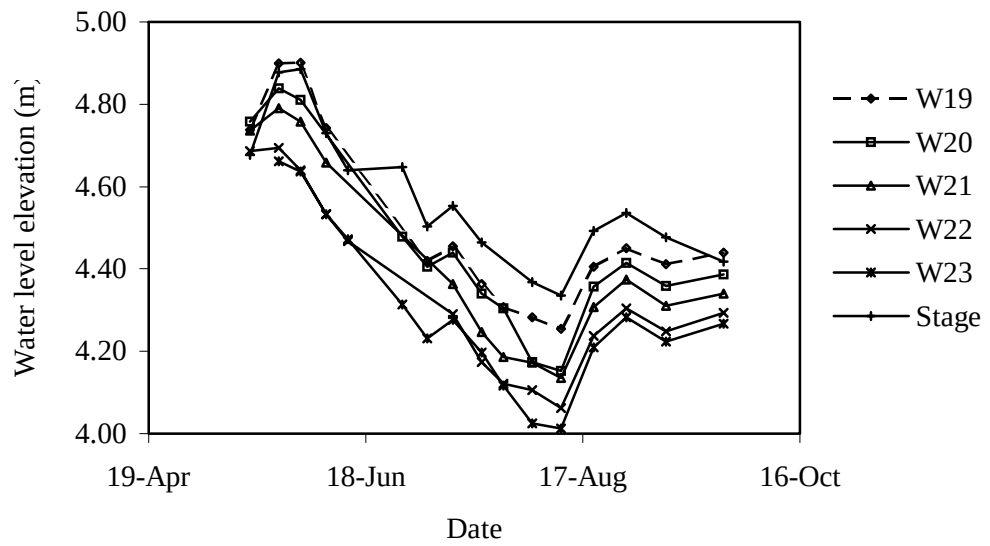
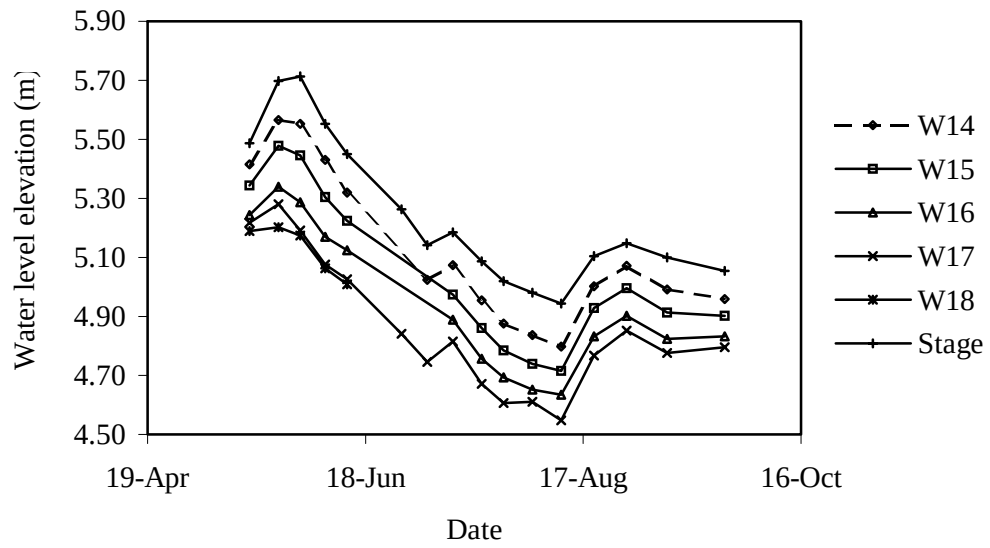


Figure 11. Stream stage and groundwater elevations at the Uruvan study site.

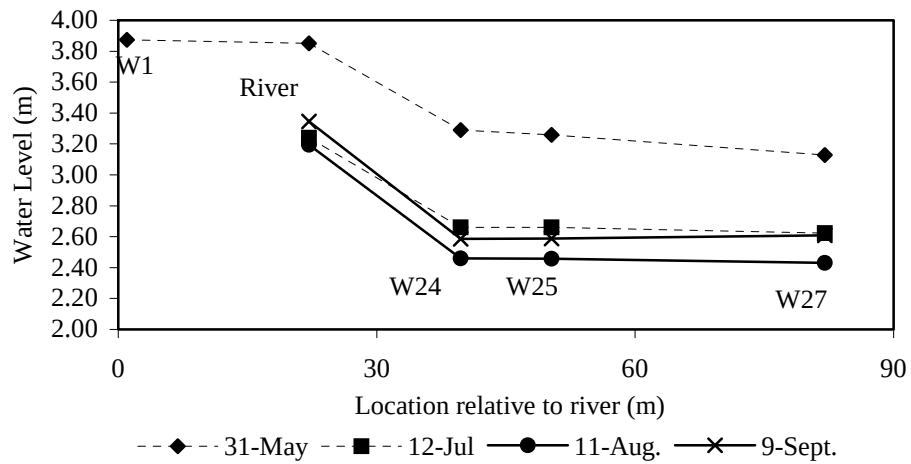
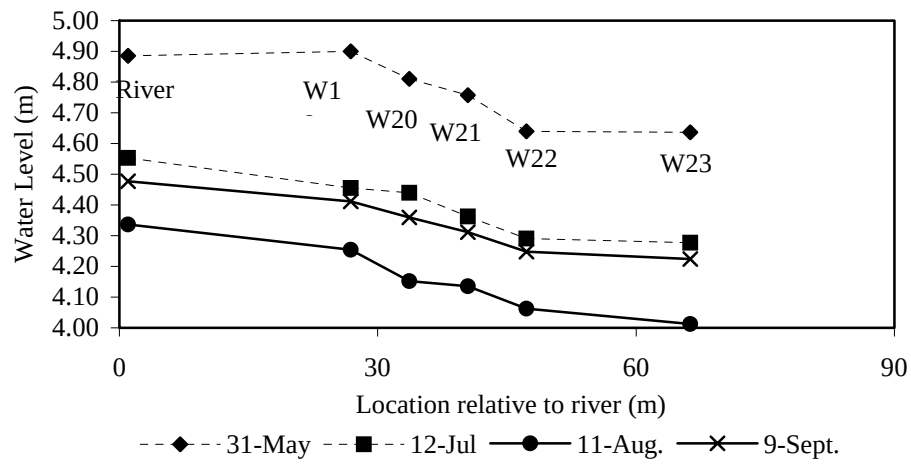
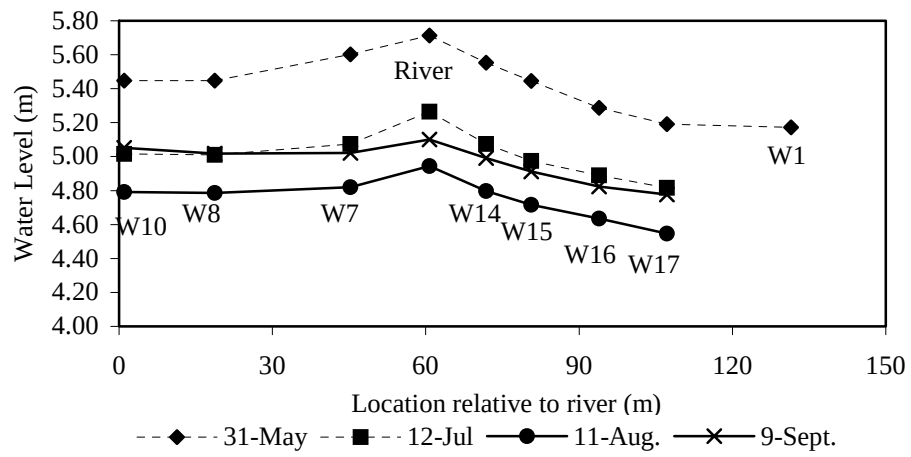


Figure 12. Groundwater elevation profiles relative to river stage at Uruvan.

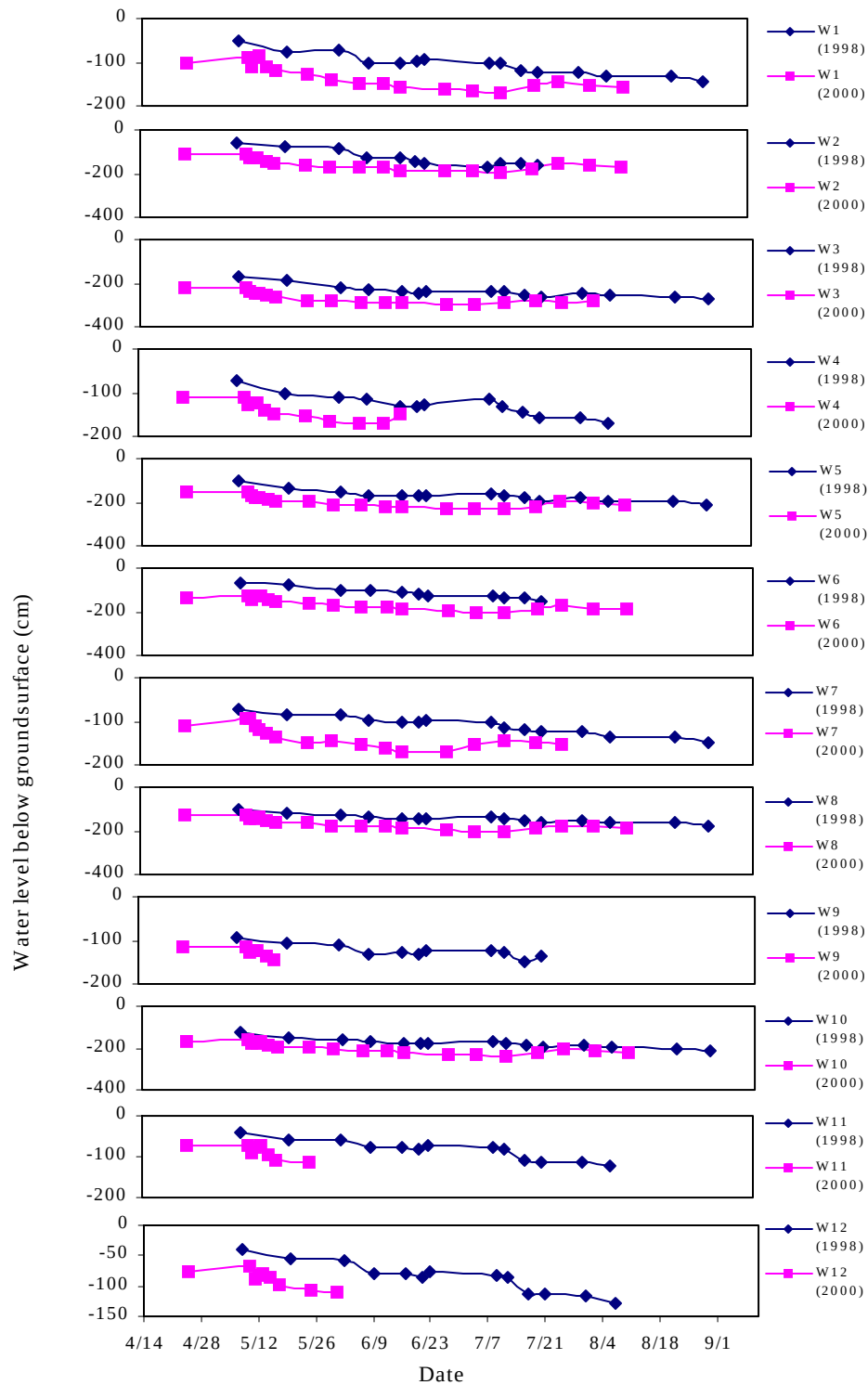


Figure 13. Comparisons of groundwater levels between 1998 and 2000 field seasons at Uraivan.

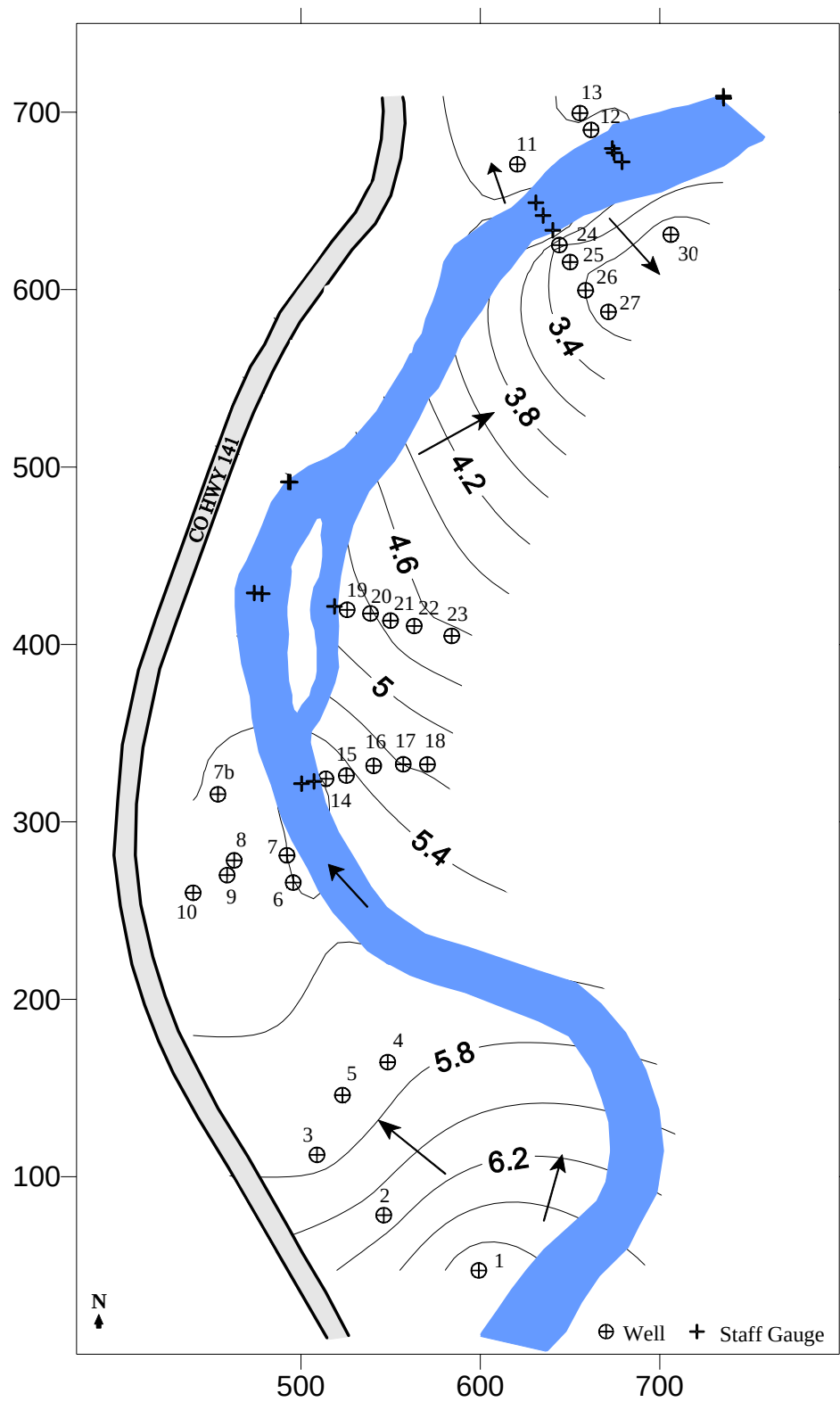


Figure 14. Water table map for the Uruvan study site on 31 May 2000. Map scale and contour elevations are in meters.

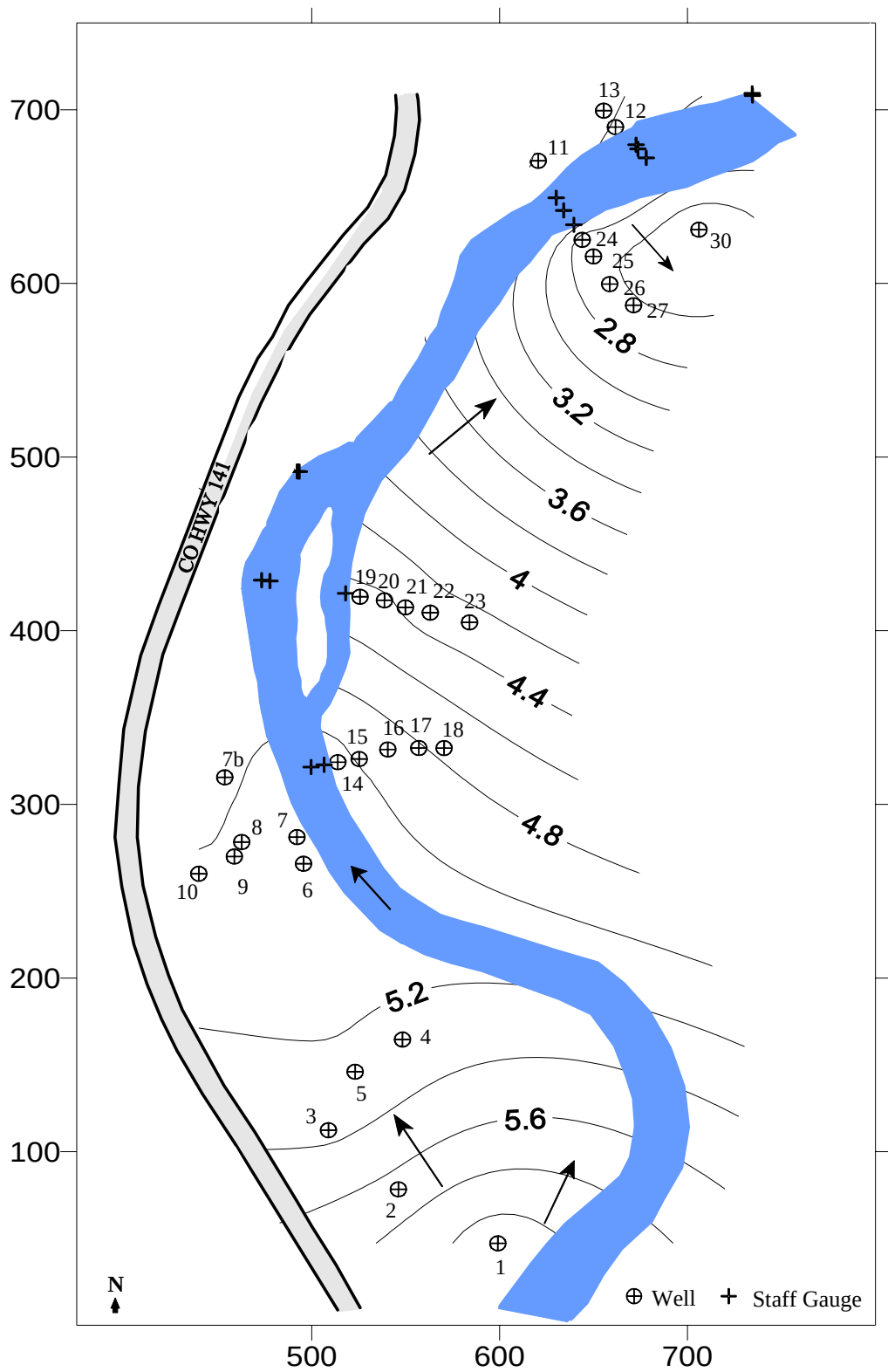


Figure 15. Water table map for the Uruvan study site on 12 July 2000. Map scale and contour elevations are in meters.

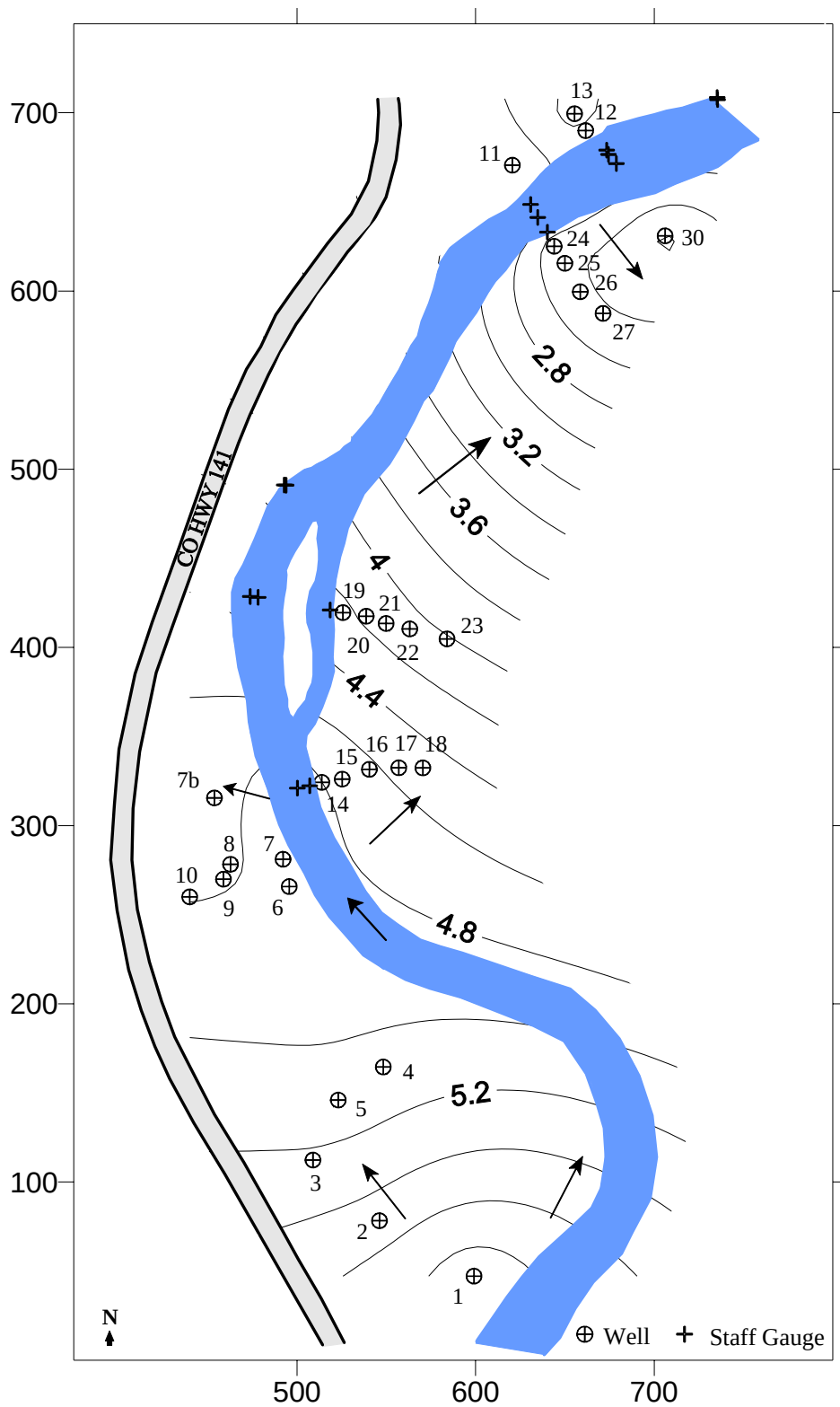


Figure 16. Water table map for the Uruvan study site on 11 August 2000. Map scale and contour elevations are in meters.

Stable Isotope Analysis of Groundwater, Tree Sap and Soils. Stable isotope data are used to determine whether the San Miguel River was the sole source of water supplying the ground water system beneath the floodplains and whether ground water was the sole water source utilized by trees during June and August at the two study sites (Figures 16, 17).

Surface Water δD . At both the Placerville and Uruvan study sites San Miguel River water was more enriched in δD in August than June indicating that water sources were being derived more from rain than winter snowpack as the summer progressed. In addition, evaporative enrichment of water in the channel was likely occurring as well.

Groundwater δD . Ground water was relatively similar in June and August at both study sites, with a δD averaging from -100 to -120 , and during August the ground water samples from the three study wells at both study sites were very similar. This indicates that while river water changed isotopically during the season, ground water changed less. During August all ground water samples are more depleted in δD than was the San Miguel River water, indicating that a water source depleted in δD was tributary to the floodplain groundwater system. Thus, ground water is being contributing to the floodplain aquifer in both study sites and even though the physical gradient of water is from the river to the floodplain.

Cottonwood Tree Sap δD . Tree sap was more enriched in δD than ground water at all sites and in both time periods (the only exception is the low site in June at Uruvan). Tree sap was most similar to soil water at the Placerville alluvial fan site during both sample times indicating that trees in that site are utilizing primarily soil water. Some soil

samples were lost in transport to the laboratory and are missing, eg. the high Placerville site in June. However, tree sap at these times is quite similar to ground water.

Trees sap at the Uruvan sites in June has δD values indicating considerable ground water acquisition, although at the intermediate site, most water may be acquired from shallow soil horizons. In August, trees at the low site were acquiring mostly soil water, while at the intermediate and high sites δD values suggest acquisition of a combination of soil and ground water.

These data suggest that three important processes are operating: (1) Groundwater δD is not identical to river water, and although our hydrologic analysis indicates that the San Miguel River is losing in many reaches, it is not the sole source of water to floodplain ground water aquifers. Clearly, ground water from adjacent hill slopes is tributary to the San Miguel River in our study reaches and influences its isotopic composition. This is especially clear in August as all three study wells in both study sites have nearly identical ground water isotope ratios, and yet none are identical to river water. (2) Trees on high landscape positions, such as the alluvial fan site at Placerville, derived most of their water from soils, which are recharged by rainwater. (3) During most of the year, plants acquired both soil water and ground water. Thus, plants utilize water available in shallow soil horizons that is recharged by rain or high spring river ground water tables, and ground water during the summer. This is most clearly seen in the August Uruvan Intermediate and High sites where tree sap δD is intermediate between ground water and soil water δD . Thus, the presence of ground water is critical to trees on the floodplain.

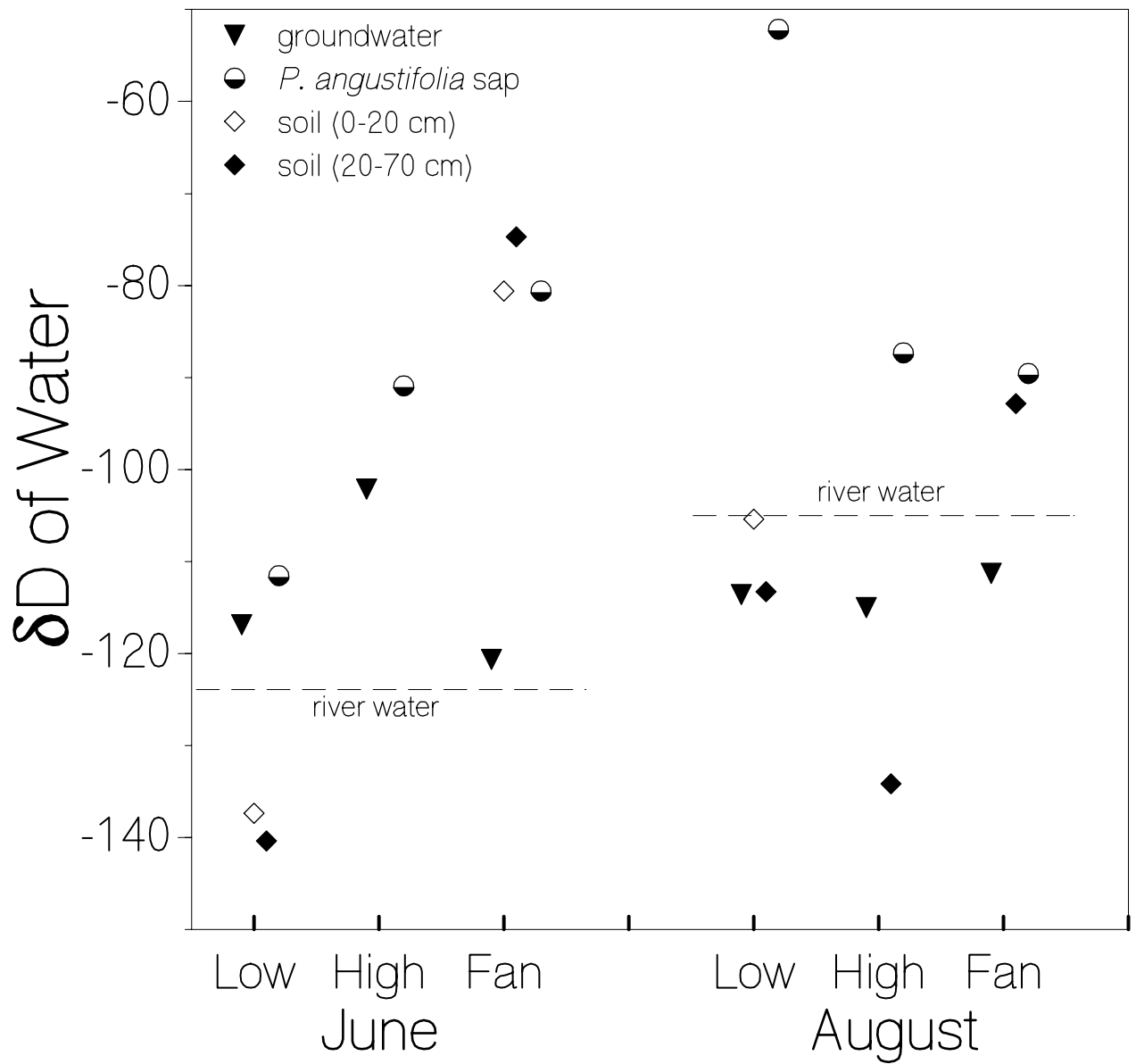


Figure 17. Mean δD values for groundwater, tree sap, and soil water for the Placerville study sites in June and August 2000.

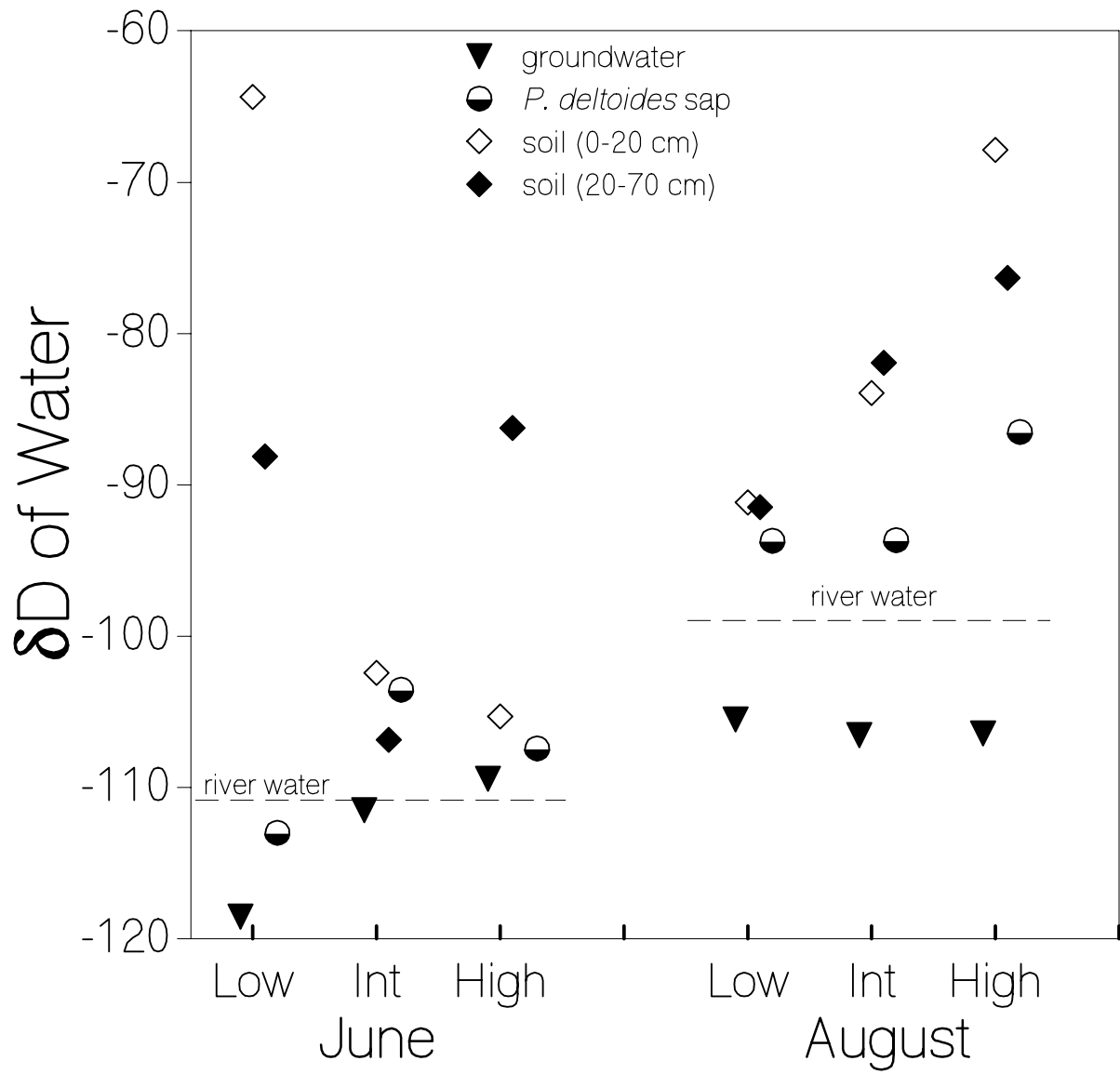


Figure 18. Mean δD values for groundwater, tree sap, and soil water for the Uruvan study sites in June and August 2000.

Cottonwood Xylem Pressure Potential. Xylem pressure potential is an important measure of the water tension in xylem vessels. Trees typically dry out during the day as water is transpired from leaves and tension in the vessels increases creating negative pressure. This is the mid-day xylem pressure potential. However, at night stomata are closed, air temperatures drop and humidity rises reducing potential evapotranspiration rates. The water potential typically recovers at night to a daily minimum, the pre-dawn water potential. The nightly recovery is an excellent indicator of whether sufficient water is available for trees. If trees do not recover at night, they are in danger of developing xylem pressures sufficient to create uncontrolled cavitation (air bubble development) in vessels, which can limit or eliminate water transport to twigs and leaves. This can lead to leaf and twig death, and if it continues long enough whole tree death.

Placerville. Data from our two sample periods at Placerville during 2000 indicate relatively water stress on trees as they recovered nightly. However, we have no data from the dry and hot period of July. Pre-dawn water potentials are in the normal range during the sample periods.

Uruvan. Xylem pressure potentials are lower at Uruvan than at Placerville during 2000. Mid-day water potentials dropped to levels similar to those measured in 1998. However, pre-dawn water potentials were lower than any we have recorded for cottonwoods on any floodplains in Colorado. Pre-dawn water potentials were -0.9 MPa during the August sample period, which is extremely low, and indicates that trees are critically water stressed.

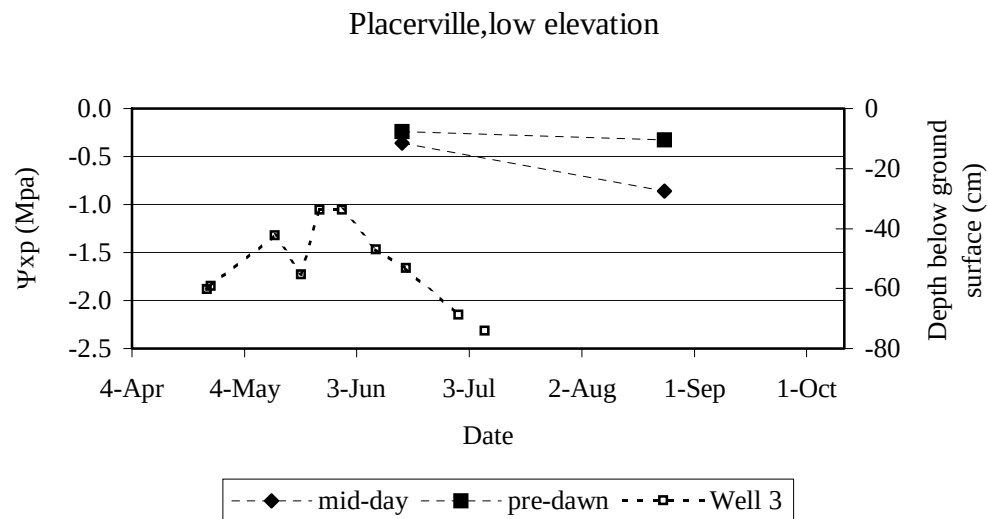
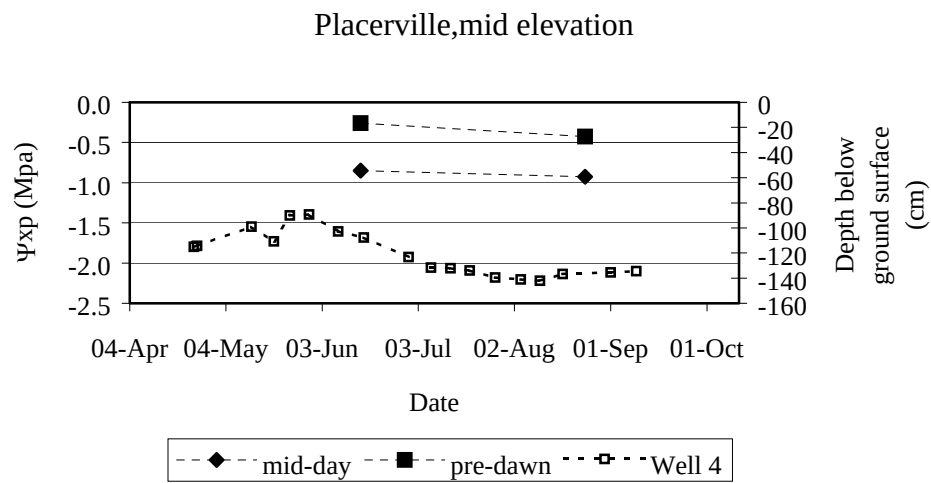
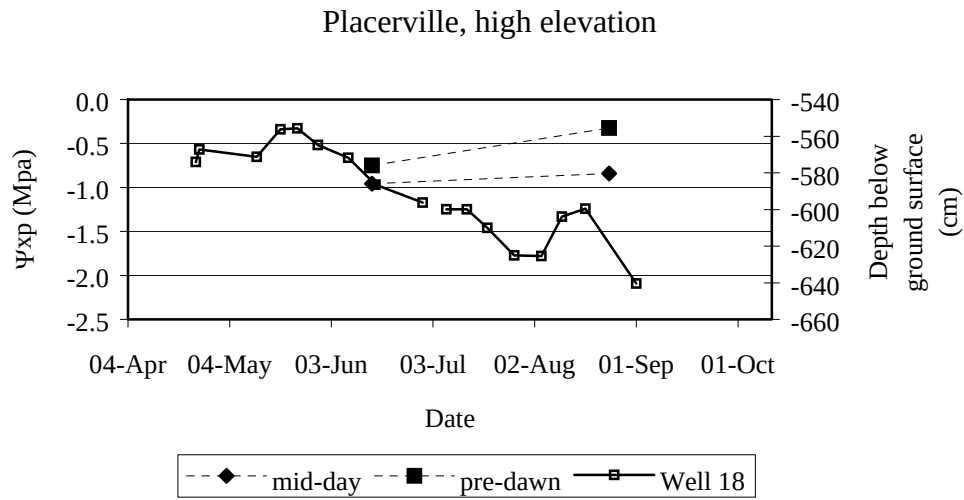


Figure 19. Ground water levels, mid-day and pre-dawn xylem pressure potentials. Water levels are depth below ground surface at measured at adjacent wells.

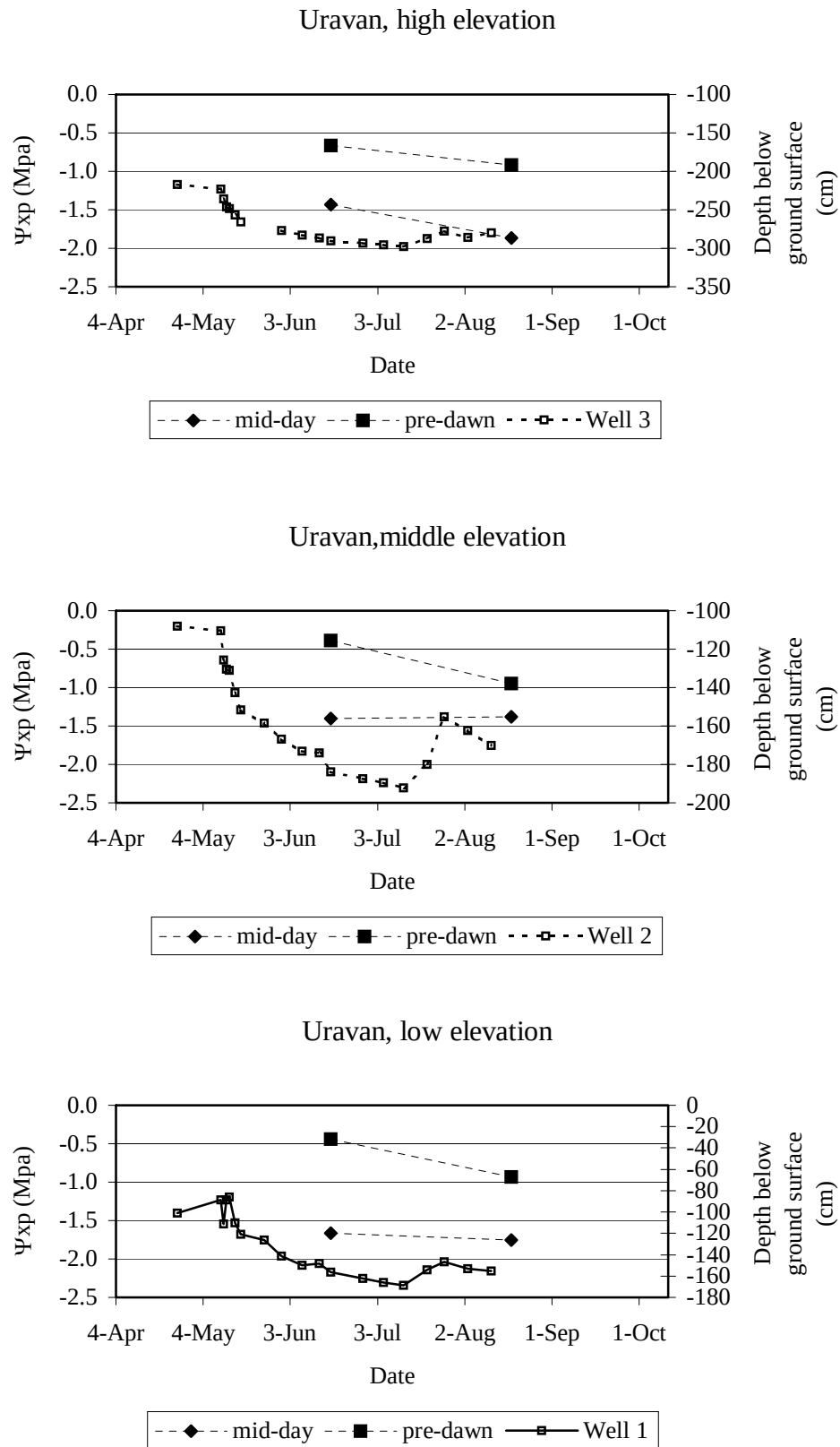


Figure 20. Ground water levels and mid-day and pre-dawn xylem pressure potentials.

DISCUSSION

Surface and Groundwater Hydrology. Our results demonstrate that the San Miguel River is a losing stream in most reaches and the floodplain groundwater elevation is controlled by river stage. However, there is evidence for hillslope groundwater inflow as indicated by the high water table elevation in the beaver pond and in well 17 at the Placerville study site. In addition, isotopic data indicates sufficient groundwater inflow alter floodplain ground water isotopic chemistry so that it is distinct from stream water at both study sites.

Changes in river stage and floodplain groundwater elevations are closely coupled. During both high and low flow periods, the difference between stream stage elevation and groundwater elevation remains relatively unchanged in both study areas. This is particularly striking in the Uruvan study site, where the relationship between surface and groundwater elevations remained stable between the peak flow of $46 \text{ m}^3/\text{s}$ in late May and the low flow of $0.5 \text{ m}^3/\text{s}$ in mid-August. Furthermore, the magnitudes of rise and fall in both river stage and groundwater levels are nearly identical. This linkage allows for the recovery of groundwater levels in August when monsoon rains typically cause an increase in streamflow.

Streamflow records suggest that minimum streamflows of approximately $2\text{-}3 \text{ m}^3/\text{s}$ in the vicinity of the Placerville study site likely are sufficient to maintain riparian vegetation in its current condition. Although San Miguel River flows have dropped below this discharge value in the past, the lowest flows occur primarily in October and later in the winter, outside of the growing season. Figure 21 plots mean daily discharge for the San Miguel River at Placerville and the timing of low flow events over the course

of the water year. Historically low flows during July rarely fall below 2-3 m³/s (Table 3). However, during August and September short duration flows below 3 m³/s are common and below 2 m³/s occur regularly. Discharge in the San Miguel River near Placerville fell below 2 m³/s for a three-day period in August 2000. However, the linkage between groundwater elevations and river stage indicates that even at this flow the wetted perimeter of the river did not decrease sufficient to change surface water recharge of the floodplain groundwater and floodplain water tables remained little changed.

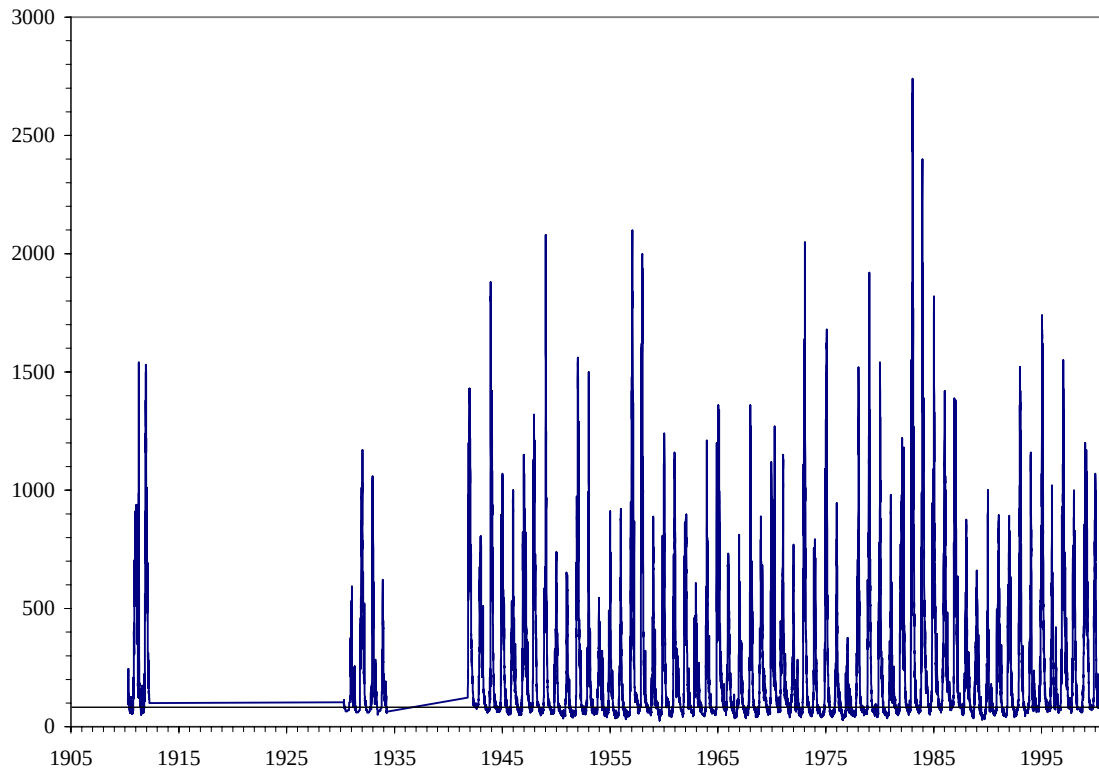


Figure 21. Historical mean daily discharge (cfs) for the San Miguel River near Placerville (data from the Placerville gauge, USGS gauge).

Table 3. July and August low-flow, duration-frequency analysis for the San Miguel River near Placerville (gage #09172500, years 1954-1998). Flow data are in m³/s.

July

Duration (days)	2 Year	5 Year	10 Year	20 Year	50 Year
3	6.3	3.9	3.1	2.6	2.1
7	6.8	4.2	3.3	2.7	2.2
14	7.6	4.7	3.7	3.0	2.5
30	10.1	6.1	4.7	3.9	3.1

August

Duration (days)	2 Year	5 Year	10 Year	20 Year	50 Year
3	3.5	2.5	2.1	1.9	1.6
7	3.9	2.7	2.3	2.0	1.7
14	4.3	3.0	2.5	2.2	1.8
30	5.2	3.5	2.9	2.5	2.2

September

Duration (days)	2 Year	5 Year	10 Year	20 Year	50 Year
3	2.6	2.0	1.8	1.6	1.5
7	2.8	2.2	1.9	1.8	1.6
14	3.1	2.3	2.0	1.9	1.7
30	3.7	2.7	2.3	2.1	1.8

Plant Water Sources and Cottonwood Tree Water Status. The stable isotope analysis of surface water, ground water, soil water and tree sap indicates that the riparian vegetation utilized both soil water and groundwater during the summer of 2000. The alluvial fan site was the only location where trees used primarily soil water. At other sites trees use both soil and groundwater and by late summer they appear to be utilizing a nearly equal mix of soil water and groundwater. This suggests that sufficient groundwater levels are critical to trees on the floodplain along the San Miguel River.

At the Uruvan study site, cottonwood pre-dawn water potentials were extremely low, -0.9 MPa, during the August sampling date, when discharge in the San Miguel River fell as low as 0.45 m³/s. Pre-dawn potentials this low indicate that trees are not

recovering at night and are in extreme danger during long drought periods of leaf, branch, and whole tree dieback. The potential long-term effects of very low summer stream flows on riparian vegetation must be more carefully examined, particularly below the CC ditch.

At the Placerville study site, our data for 2000 indicate that the trees were not unduly stressed during the sample periods and that the measured pre-dawn water potentials were in the normal range. We did not collect data during the driest period in July, however the measurement period in August was taken during a period of low streamflow with less than average monsoonal precipitation for that time of year.

Conclusions

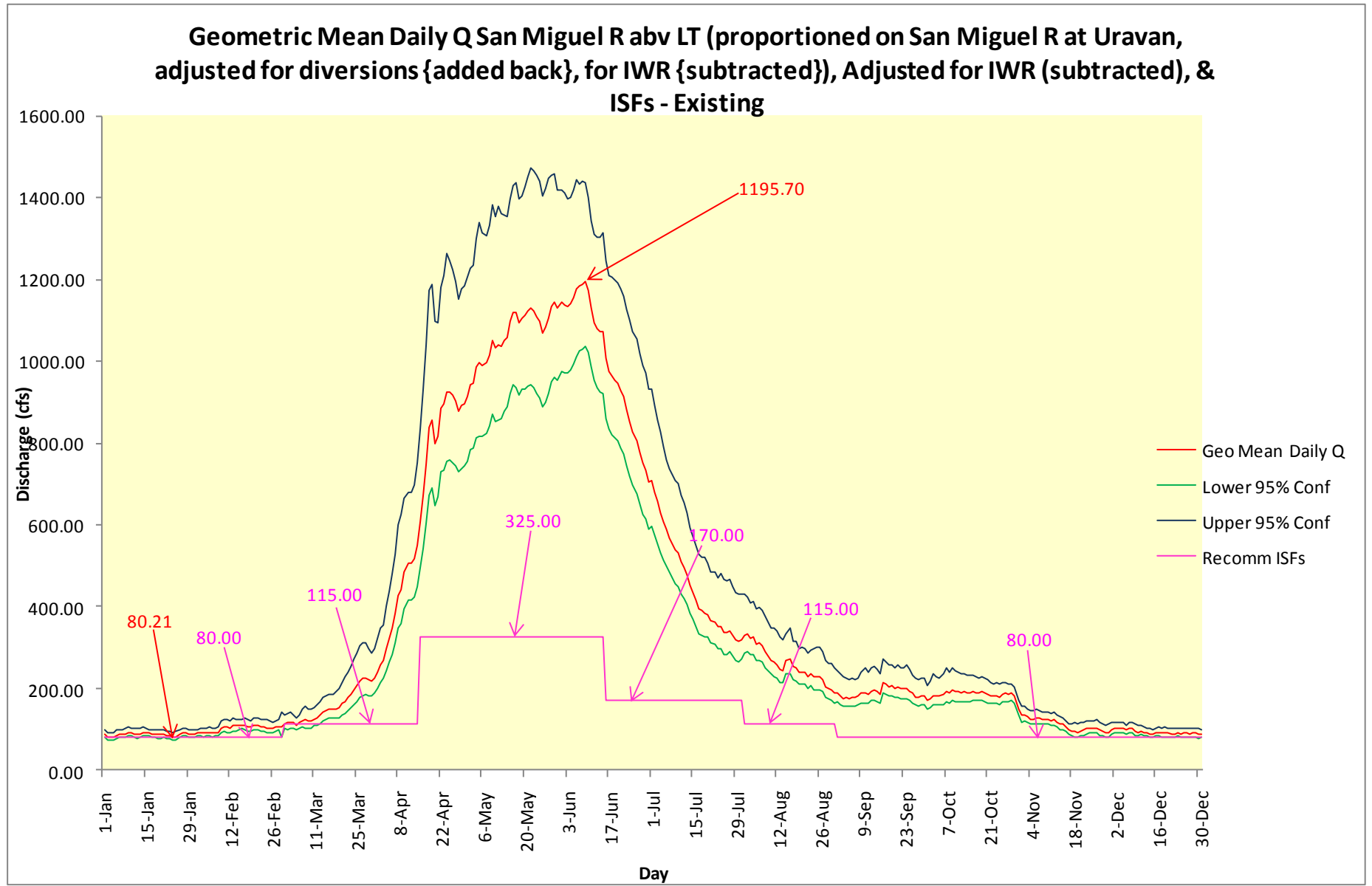
Our research further supports the conclusions of Cooper and Arp (1999) that floodplain groundwater levels are controlled by river stage and that the San Miguel River is the main source of water for the adjacent floodplain aquifers. Furthermore, groundwater levels and river stage are tightly coupled. Trees on the floodplain acquire water from both groundwater and soil water sources, and the groundwater within the floodplain is fed from both the river and hillslope sources.

Cottonwood trees at the Uruvan study site are in danger of uncontrolled cavitation and dieback during periods of prolonged drought, which could be exacerbated if San Miguel River base flows are decreased. The hydrologic and ecological data collected from the Placerville study site suggest that the riparian vegetation within the floodplain are under less stress, and that a proposed instream minimum flow value of $2.5 \text{ m}^3/\text{s}$ would be adequate in maintaining a healthy riparian zone if the duration of these low flows was similar to historic low flow durations.

References Cited

- Cooper D.J. and C.D. Arp. 1999. Riparian Vegetation of the Middle and Lower San Miguel River: Surface and Groundwater Interactions, Plant Water Sources, Plant Water Status, and Susceptibility to Impacts from Changing River Base Flows. Report submitted to the Bureau of Land Management, Montrose district office.
- Ehleringer, J.R. and C.B. Osmond. 1989. Stable Isotopes. In: Plant Physiological Ecology, edited by: Pearcy, R.W., J.R. Ehleringer, H.A. Mooney, and P.W. Rundel. Chapman and Hall, N.Y., pp. 281-300.
- Fleener, G.B. 1997. Hydrologic and Geomorphic Aspects of Riparian Forest Ecology on the Lower San Miguel River, CO. PhD Dissertation, University of Colorado at Boulder, 139 pp.
- Weber, W.A. and R.C. Whittman. 1996. Colorado Flora: Western Slope, revised edition, *University Press of Colorado*, Niwot, CO.

Figure 1



Stream: SAN MIGUEL RIVER

Executive Summary

Water Division: 4

Water District: 60

CDOW#: 46842

Segment: CALAMITY DRAW to DOLORES RIVER

Upper Terminus: CALAMITY DRAW

Latitude: 38° 15' 24.0"N Longitude: 108° 36' 49.5"W

Lower Terminus: DOLORES RIVER

Latitude: 38° 22' 47.1"N Longitude: 108° 48' 12.3"W

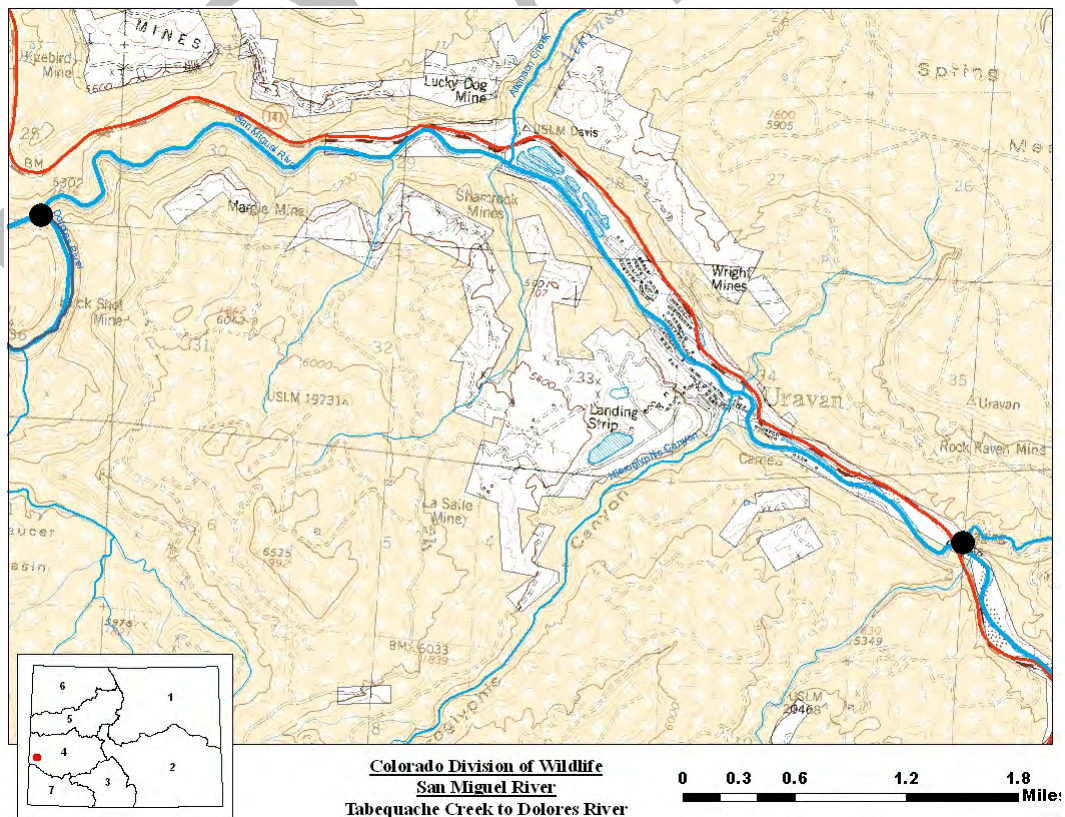
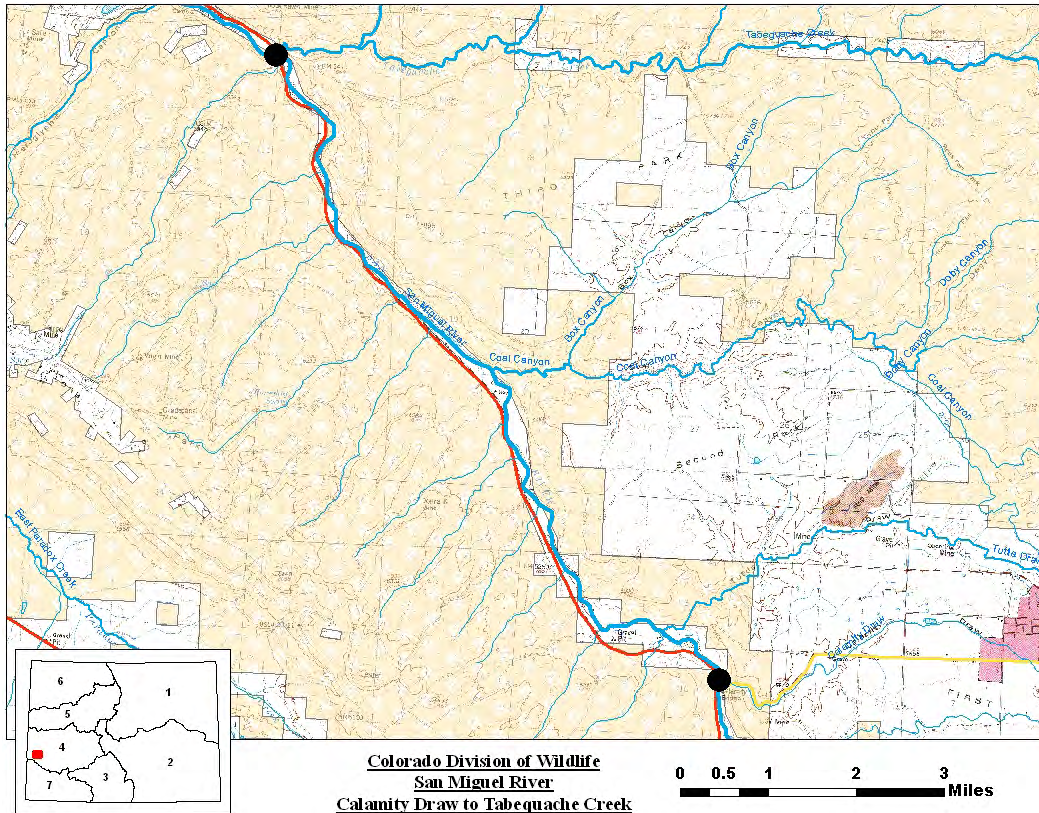
Counties: Montrose County

Length: 16.5 miles

USGS Quad(s):

ISF Appropriation: 325 cfs (04/15 – 06/14) – (Uravan Gage)
 170 cfs (06/15 – 07/31)
 115 cfs (08/01 – 08/31)
 80 cfs (09/01 – 02/28)
 115 cfs (03/01 – 04/14)





The information contained in this report and the associated instream flow file folder forms the basis for the instream flow recommendation to be considered by the Colorado Water Conservation Board (Board). It is the Colorado Division of Wildlife (CDOW) and Bureau of Land Management (BLM) staff's opinion that the information contained in this report is sufficient to support the findings required in Rule 5(i).

The State of Colorado's Instream Flow Program (ISFP) was created in 1973 when the Colorado State Legislature recognized "the need to correlate the activities of mankind with some reasonable preservation of the natural environment" (See §37-92-102 (3) C.R.S.). The statute vests the Board with the exclusive authority to appropriate and acquire instream flow and natural lake level water rights. In order to encourage other entities to participate in Colorado's ISFP, the statute directs the Board to request instream flow recommendations from other state and federal agencies. The CDOW & BLM are jointly recommending this segment of San Miguel River to the Board for inclusion into the ISFP. The San Miguel River is being considered for inclusion into the ISFP because it has a natural environment that can be preserved to a reasonable degree with an instream flow water right.

The CDOW is forwarding this instream flow recommendation to the Board to meet Colorado's policy "... that the wildlife and their environment are to be protected, preserved, enhanced, and managed for the use, benefit, and enjoyment of the people of this state and its visitors ... and that, to carry out such program and policy, there shall be a continuous operation of planning, acquisition, and development of wildlife habitats and facilities for wildlife-related opportunities" (See §33-1-101 (1) C.R.S.). The CDOW Strategic Plan states "[h]ealthy aquatic environments are essential to maintain healthy and viable fisheries, and critical for self-sustaining populations. The [CDOW] desires to protect and enhance the quality and quantity of aquatic habitats."

The Bureau of Land Management is forwarding this instream flow recommendation to the Board because it is strongly interested in instream flow protection for the lower San Miguel River for multiple reasons. First, this portion of the river is known to provide habitat for flannemouth sucker, bluehead sucker, and roundtail chub. The BLM, CDOW and others have signed a multi-state conservation agreement designed to protect and enhance habitat for these species, with the objective of preventing a listing of these species under the Endangered Species Act (see Appendix _). Establishment of instream flow protection for streams known to provide habitat for the species is identified as a priority conservation action under this agreement.

Second, the lower San Miguel River is known to provide habitat for globally imperiled riparian communities and other important riparian communities, because of the free-flowing hydrology of the river. These globally impaired communities include New Mexico Privet riparian shrubland and Skunkbrush riparian shrubland. Other important riparian communities include Narrowleaf Cottonwood Communities and Fremont Cottonwood communities. The Colorado Natural Heritage Program has identified two potential conservation areas along this reach of the river because of these riparian communities and species. Finally, BLM seeks to protect flows that support reclaimed acreage from the Umetco Superfund site. The reclamation effort is now complete, and the flows assist in maintaining the ecology of land parcels that were donated by Umetco as part of the Superfund settlement.

General Information

The San Miguel River is approximately 70 miles long. It begins on the north side of Wasatch Mountain at an elevation of approximately 9100 feet and terminates at the confluence with the Dolores River at an elevation of approximately 4900 feet. Of the 16.5 mile segment addressed by this report, approximately ___% of the segment, or ___ miles, is located on public lands. The San Miguel River is located within San Miguel and Montrose Counties. The total drainage area of the San Miguel River is approximately 1,500 square miles. The San Miguel River generally flows in a westerly direction. The San Miguel Basin is the largest tributary to the Dolores River and is part of the Upper Colorado River System. The one million acre San Miguel Basin is about 60 percent semi-arid rangeland and agricultural land, both comprising the lower elevations. The remaining 40 percent of the basin is in higher elevation, forested subalpine and alpine zones of the San Juan Mountains. Most of the flow in the San Miguel River (240,000 acre-feet per year) is derived from snowmelt at the higher elevations. Because of its relatively low, human population density and lack of large, water storage impoundments, the San Miguel Basin is considered to be one of the few ecologically and hydrologically intact river basins in Colorado (BLM Chap2)

The subject of this report is two segments of the San Miguel River. The first segment begins at the confluence with Calamity Draw and extends downstream to the confluence with Tabeguache Creek. The second segment begins at Tabeguache Creek and extends downstream to the confluence with the Dolores River. The proposed segments are located west of the towns of Nucla and Naturita. The instream flow recommendation for both segments is discussed below.

Species of Special Concern and Sensitive Species

Roundtail chub (*Gila robusta*) is recognized by the State of Colorado as a species of special concern. The roundtail chub, flannelmouth sucker (*Catostomus latipinnis*) and bluehead sucker (*Catostomus discobolus*) are considered sensitive species by the BLM. Criteria that apply to BLM sensitive species include the following: 1) species under status review by the U.S. Fish and Wildlife Service; or 2) species with numbers declining so rapidly that federal listing may become necessary; or 3) species with typically small and widely dispersed populations; or 4) species inhabiting ecological refugia or other specialized or unique habits.

The CDOW, BLM and others have developed a “Range-wide conservation agreement and strategy” to direct management for these species. This plan provides direction and goals for research and management of projects. The success of management strategies will depend upon the voluntary implementation of these strategies by the signatories. Special attention will need to be given to habitat degradation and influence of non-native species interactions within the native range of these species. The intention of these plans is to increase populations and distributions of identified species, thereby assisting in the long-term persistence of each species. The success of such plans could potentially curtail the need for federal listing of these species under the Endangered Species Act (ESA). These species are not currently federally listed.

ROUNDTAIL CHUB

Historically, roundtail chub were known to commonly occur in most medium to large tributaries of the Upper Colorado River Basin (Vanicek 1967, Holden and Stalnaker 1975, Joseph et al. 1977). Roundtail chub historically occurred in lower elevation (below 7,546 ft.) streams, including the Colorado, Dolores, Duchesne, Escalante, Green, Gunnison, Price, San Juan, San Rafael, White, and Yampa rivers (Bezzerrides and Bestgen 2002). Roundtail chub are often found in stream reaches that have a complexity of pool and riffle habitats (Bezzerrides and Bestgen 2002). Adults are found in eddies and pools adjacent to strong current and use instream boulders as cover (Sigler and Sigler 1996, Brouder et al., 2000). Roundtail chub begin spawning when water temperatures reach about 65°F (Vanicek and Kramer 1969, Joseph et al. 1977). In most Colorado River tributaries this increase in temperature coincides with a decrease in discharge after peak runoff (Bezzerrides and Bestgen 2002).

FLANNELMOUTH SUCKER

The flannemouth sucker is a good indicator species for flow and habitat relationships (Stewart and Anderson 2006-CR1). The flannemouth sucker is a large fish reaching up to almost 2 feet in length. Historically, the flannemouth sucker was commonly found in most, if not all, medium to large, lower elevation rivers of the Upper Colorado River drainage (upstream of Glen Canyon Dam). Within the State of Colorado, flannemouth sucker are present in the Colorado River and numerous tributaries including the Gunnison River up to the Aspinall Unit reservoirs (Bezzerrides and Bestgen 2002), the Uncompahgre River (Sigler and Miller 1963) and the Dolores River. Flannemouth suckers are typically found in slower, warmer rivers in plateau regions of the Colorado River drainage (Deacon and Mize 1997). They usually inhabit the mainstem of moderate to large rivers but are occasionally found in small streams. This species frequents pools and deep runs but can also be found in the mouths of tributaries, riffles, and backwaters. Flannemouth sucker typically spawn in the Upper Colorado River basin between April and June (McAda 1977, McAda and Wydoski 1980, Snyder and Muth 1990, Tyus and Karp 1990).

BLUEHEAD SUCKER

The bluehead sucker provides the most information for justifying instream flow needs to maintain the native fish assemblage (Stewart and Anderson 2006-CR1). The bluehead sucker is a large fish reaching up to 17 inches in length. This species is found in a large variety of river systems ranging from large rivers with discharges of several thousand cfs to small creeks with less than a couple of cfs (Smith 1966). Adult bluehead suckers exhibit a strong preference for specific habitat types (Holden and Stalnaker 1975). This species has been reported to typically be found in runs or riffles with rock or gravel substrate (Vanicek 1967, Holden and Stalnaker 1975, Carlson et al. 1979, Sublette et al. 1990). The bluehead sucker is known to feed on invertebrates, which have their highest densities in riffles. Although the species generally inhabits streams with cool temperatures, bluehead suckers have been found inhabiting small creeks with water temperatures as high as 82.4° F (Smith 1966).

Instream Flow Recommendation(s)

The CDOW & BLM are recommending 325 cfs, high flow period (spring/summer), and 115 cfs, low flow period (fall/winter), based on their data collection efforts. These flow recommendations are based on the physical and biological data collected to date and do not incorporate any water availability constraints.

- 325 cubic feet per second is required to maintain a reasonable amount of bluehead and flannemouth sucker usable spring and summer habitat, in addition to maintaining the three principal hydraulic criteria of average depth, average velocity and percent wetted perimeter at adequate levels;
- 115 cubic feet per second is required to maintain a reasonable amount of bluehead and flannemouth sucker usable fall and winter habitat, in addition to maintaining two of the three principal hydraulic criteria.

The recommended flow values were determined using the best professional judgment of CDOW and BLM biologists and hydrologists. The CDOW and BLM professionals reviewed and evaluated the results of the Physical Habitat Simulation (PHABSIM) Methodology and RHABSIM software PHABSIM/RHABSIM analysis. They also reviewed the R2CROSS analysis, using standard hydraulic criteria.

Land Status Review

Upper Terminus	Lower Terminus	Total Length (miles)	Land Ownership	
			% Private	% Public
CALAMITY DRAW	TABAUCHE CREEK	10.0	—	—
TABAUCHE CREEK	DOLORES RIVER	6.5		

— % of the public lands are managed by the BLM.

Biological Data

Over the past ten years, the CDOW and BLM have been collecting stream cross-section information, natural environment data, and other data needed to quantify the instream flow needs for this reach of the San Miguel River. The San Miguel River is classified as a large river (over 100 feet wide) and fishery surveys in 2001 indicate the stream environment supports: bluehead sucker (*Catostomus discobolus*), flannemouth sucker *Catostomus latipinnis*, mottled sculpin (*Cottus bairdi*), roundtail chub (*Gila robusta*), speckled dace (*Rhinichthys osculus*) and white sucker (*Catostomus commersoni*) (See CDOW Fish Survey in Appendix _).

In addition, the BLM has been collecting aquatic invertebrate samples, for several years, at several sites within the proposed instream flow reaches. These sites include the San Miguel upstream of the Dolores, at Tabeguache Creek and upstream of Tabeguache Creek (see Appendix _).

Biological and Field Survey Data

The CDOW and BLM collected transect and flow data for 7 different cross-sections within an 815 foot reach of stream. The transect data was collected at a site approximately 1.5 miles upstream from the confluence of the San Miguel River with Tabeguache Creek. These 7 transects incorporated different mesohabitat types including riffles, runs, pools and glides. These 7 different cross-sections formed the basis for the PHABSIM/RHABSIM study conducted by the CDOW and BLM. PHABSIM is widely used in North America to quantify instream flow

regimes and consists of two modeling components. The hydraulic component is a series of one-dimensional cross-sections that are linked to produce a series of rectangular cells that form a grid. Mean depth and velocity conditions are calculated for each cell for a given flow. The biological component is a set of suitability index curves for depth and velocity criteria that are used to rate micro-habitat suitability for each cell in the cross-sectional grid. Habitat availability is measured by an index called weighted useable area (WUA)¹, the summation of cell areas weighted by its suitability index. When plotted versus discharge WUA typically peaks at a single flow that is considered the flow that maximizes habitat. Please see appendix _ for more information on the PHABSIM Methodology.

For this study, 7 one-dimensional cross-sections were linked to produce the series of rectangular cells that formed the grid to estimate WUA. Mean depth and velocity conditions were calculated for each cell at 4 different measured flows (100, 175, 325 and 450 cfs). Habitat suitability criteria (HSC) were developed from the 2003 Riverine Fish Flow Investigation Study Report (Federal Aid Project F-289-R6) written and performed by Richard Anderson, CDOW Aquatic Researcher, and Gregory Stewart, Department of Geosciences Oregon State University². The basis for this study was a 1999 request from the CWCB for the CDOW to provide biologically justified instream flow recommendations for the Yampa and Colorado Rivers based on habitat and flow requirements for non-endangered native fish. Anderson and Stewart used two-dimensional (2D) modeling to develop habitat suitability criteria for bluehead and flannemouth suckers, two native species. Their methods and results are more fully described in Anderson and Stewart (2003) and Stewart and Anderson (2005) and (2006).

The bluehead and flannemouth sucker habitat suitability criteria were used to develop specific hydraulic criteria that were incorporated into a PHABSIM/RHABSIM analysis.. Stewart and Anderson determined that “Abundance of bluehead sucker was a reliable indicator for instream flows and habitat maintenance for the native fish assemblage. In the Colorado, Gunnison and Yampa Rivers bluehead sucker habitat peaked at flows of 600 to 1,200 cfs. This flow range also resulted in high habitat diversity and high native fish biomass. Their assumption that flows that maintained adequate bluehead sucker abundance (about 25% of fish over 15 cm) would also maintain adequate flannemouth sucker and roundtail chub habitat was validated by this study.”

CDOW and BLM determined for this flow recommendation that the bluehead sucker would be the primary indicator species for the biologically based instream flow recommendation with the flannemouth sucker being the secondary indicator species. The main reason for this is bluehead sucker abundance is directly related to availability and quality of riffle habitats. The primary objective of most cross section methodologies, including R2CROSS, is to maintain quality riffles. Riffles are the most vulnerable habitat to dewatering and riffles are important for invertebrate productivity. When riffle habitats are maintained there should be sufficient habitats for perpetuating carrying capacity (biomass) and composition for all members of the native fish assemblage (Nehring 1979). To verify the flow recommendations, CDOW and BLM compared results from their PHABSIM/RHABSIM study with results using the R2CROSS Methodology with standard criteria (see Appendix _).

¹ No Channel Material Indexes were used to quantify the WUA in this report.

² See “Impacts of stream flow alterations on native fish abundance and native fish habitat and the use of native fish population data to support instream flow recommendations made using a 2D instream flow methodology.”

Transect 1 was located within a typical riffle section and was used in a standard R2CROSS analysis. The modeling results from these efforts are within the confidence interval produced by the R2CROSS model (see Table 1).

Biological Flow Recommendation

CDOW and BLM staff, using a combination of PHABSIM/RHABSIM and R2CROSS methodologies, developed the proposed instream flow recommendations for the San Miguel River (see Appendix _ for copies of the field data). Board staff relied upon the biological expertise of the cooperating agencies to interpret the output from the PHABSIM/RHABSIM and R2CROSS Methodologies to develop the initial, biologic instream flow recommendations.

These initial recommendations are designed to address the unique biologic requirements of each stream without regard to water availability. In addition to the criteria developed using the PHABSIM Methodology and RHABSIM Software, the three standard instream flow hydraulic parameters used in R2CROSS (average depth, percent wetted perimeter and average velocity) were also used to calculate and predict the biologic instream flow recommendations (see Table _ Below).

For this segment of stream, several data sets were collected with the results shown in Table 1 below. Table 1 shows who collected the data (Party), the measured discharge at the time of the surveys (Q), the accuracy range of the predicted flows based on Manning's Equation (240% and 40% of Q), the method used, the summer flow recommendation based on meeting 3 of 3 hydraulic criteria and the winter flow recommendation based upon 2 of 3 hydraulic criteria.

Table 1: Data

Party	Measured Q's	250%-40%	Method	Summer (3/3)	Winter (2/3)
DOW & BLM	450, 325, 175, 100	1125 - 40	PHABSIM / RHABSIM	500 (Bluehead) 325 (Flannelmouth) ³	---
DOW & BLM	450, 325, 175, 100	1125 - 40	R2X Standard	650	115

DOW = Division of Wildlife; BLM = Bureau of Land Management

Biologic Flow Recommendation

The CDOW and BLM evaluated all of the data collected to date and determined that best flow recommendation would come from using the results from a combination of methods. PHABSIM is a widely accepted method for quantifying the suitable versus unsuitable hydraulic habitat attributes of selected species and life stages as a function of discharge. R2CROSS is best suited for identifying flows with specific hydraulic criteria across riffle type habitats. The State of Colorado has used R2CROSS extensively in the past to appropriate instream flow water rights. CDOW and BLM were concerned that the standard R2CROSS method may not be appropriate

³ The PHABSIM/RHABSIM analysis was used to only quantify the suitable versus unsuitable hydraulic habitat attributes of bluehead and flannelmouth sucker adults as a function of discharge. Amounts shown reflect the discharge which produced the maximum amount of useable habitat based on the measured mesohabitat types.

for this reach of the San Miguel River due to its major width (over 75' wide in most places), type of fish species present (warm/cool water species) and its big river channel hydraulics and characteristics.

Accordingly, BLM and CDOW staff compared results from their PHABSIM/RHABSIM data analysis with their R2CROSS analysis. Using the results from the PHABSIM/RHABSIM data analysis, the maximum amount of usable habitat for bluehead suckers was produced at a flow of 500 cfs and for flannemouth suckers at a flow of 325 cfs. The R2CROSS analysis indicated that a spring/summer flow of approximately 650 cfs was necessary to meet all three of the critical hydraulic criteria at this site and a fall/winter flow of 115 cfs would meet 2 of 3 of the hydraulic criteria.

CDOW and BLM are recommending that a flow of 325 cfs, for the time period of April 15 through June 14, is the minimum amount necessary to preserve the natural environment to a reasonable degree, for this reach of the San Miguel River. This is based on the assumption that 325 cfs would preserve 90% of the weighted useable area available to the bluehead sucker and 100% of the weighted useable area available to the flannemouth sucker. BLM and CDOW staff also believe a flow that maintains adequate bluehead and flannemouth sucker habitat should also maintain adequate roundtail chub habitat. The spring/summer flow of 325 cfs was reduced to 170 cfs for the June 15 through July 31 time period because of water availability concerns. The instream flow recommendation of 170 cfs was derived to maximize the existing bluehead and flannemouth sucker habitat available under a declining hydrograph, by maintaining an average depth of 1.0 foot over the measured riffle cross-section. An average depth of 1.0 foot combined with average velocities exceeding 1.3 ft/sec, were determined to be marginally suitable bluehead sucker habitat (see Anderson & Stewart Report).

Because the PHABSIM/RHABSIM data only quantified suitable versus unsuitable hydraulic habitat as a function of discharge, CDOW and BLM staff used the results of the R2CROSS Method to develop the fall/winter instream flow recommendation of 115 cfs. The R2CROSS Method suggests that fall/winter flows should maintain at least 2 of 3 of the identified critical hydraulic criteria. At the Cross Section #1 site, 115 cfs meets 2 of 3 criteria (average depth and velocity) by providing on average, 0.8 feet of depth and velocities well over 1.0 ft/sec. The fall/winter flow recommendation was further reduced to 80 cfs, for the time period of September through February, due to water availability concerns. It should be noted however, that 80 cfs still maintains adequate velocity (approximately 2.5 ft/sec), a wetted perimeter of almost 60% and an average depth of nearly 0.7 feet.

Hydrologic Data

The BLM and CDOW staff conducted an evaluation of the stream hydrology to determine if water was physically available for the instream flow recommendation. The hydrograph below was derived from data collected by the USGS stream gage for the San Miguel River at Uravan, CO (#09177000), which has a drainage area of 1500 square miles (See Gage Summary in Appendix C). The total drainage area of this segment of the San Miguel River is approximately 1500 square miles. The period of record for this gage was 1954 to 2004, the period of record used by staff in their analysis was 1954 - 2004, or 50 years of record. Table 2 below displays the estimated flow of the San Miguel River at the gage, in terms of a percentage of exceedence.

Table 2: Estimated Stream Flow for SAN MIGUEL RIVER

Exceedences	January	February	March	April	May	June	July	August	September	October	November	December
1%	162.9	351	1044	3750	4123	2808	1770	958.5	612	432	370.6	217.8
5%	140	186.1	578.2	2610	2700	2240	1102	597.2	371	292.1	212	160
10%	130	155.7	383.2	1900	2220	1770	868	424.7	301	252	182	148
20%	120	130	252	1260	1724	1380	633.4	265.6	201	199	152	121
50%	80	97	128	550	943	820	301	125.5	88	116	100	85
80%	62	70	83	233	484	437	112	51.2	42	76.6	73	65
90%	55	61	70.8	130	271	298	61	27	29	53.8	61	57
95%	48	55	62	96	140.9	215	34	20.55	23	33	52	50
99%	40	40.73	47	55	61.9	38	6.63	5.91	14	20	32	36

Table 2 shows that the spring flow recommendation of 325 cfs is available at least 50% of the time April 15 through June 30. The high flow summer recommendation of 170 cfs is available at least 50% July 1 through July 31. The low flow summer recommendation of 115 cfs is available at least 50% August 1 through August 31 and March 1 through April 14 and the winter recommendation, reduced based on water availability concerns, of 80 cfs is available at least 50% September 1 through February 29. However, if additional water is determined to be available in further investigations, the CDOW and BLM would recommend enlarging the wintertime recommendation up to 115 cfs to preserve the natural environment to a reasonable degree.

Precipitation Data

CDOW and BLM staff identified _ local precipitation data sets located near the San Miguel River Drainage: _____ (see Precipitation Data in Appendix C).

Existing Water Right Information

CDOW and BLM staffs have analyzed the water rights tabulation and will consult with the Division Engineer's Office (DEO) to identify any potential water availability problems due to existing diversions. The upper terminus for the proposed instream flow reaches, Calamity Draw, was selected because it is the location where significant return flows accrue to the river from lands irrigated by the CC Highline Canal.











