BEFORE THE COLORADO WATER CONSERVATION BOARD

STATE OF COLORADO

Prehearing Statement of the United States of America, Department of the Interior, Bureau of Land Management

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IN THE MATTER OF STAFF'S RECOMMENDATIONS FOR AN INSTREAM FLOW APPROPRIATION ON MILK CREEK BETWEEN THE CONFLUENCE WITH WILSON CREEK AND THE CONFLUENCE WITH THE YAMPA RIVER, WATER DIVISION 6

Pursuant to Rule 5n(2) of the Rules Concerning the Colorado Instream Flow and Natural Lake Level Program ("ISF Rules"), the Bureau of Land Management ("BLM") hereby submits its prehearing statement in support of the Colorado Water Conservation Board ("CWCB") staff's recommendations for an instream flow appropriation on Milk Creek between the confluence with Wilson Creek and the confluence with the Yampa River. BLM supports the appropriation on the reach in the locations, timing, and amounts adopted by the CWCB at its March 2025 regularly scheduled board meeting. The CWCB adopted the locations, timing, and amount set forth in the CWCB staff recommendation report made available to the CWCB and the public at the March 2025 CWCB board meeting. An executive summary of this recommendation is available for review on the CWCB's website at 2025 ISF Recommendations | DNR CWCB).

A. FACTUAL CLAIMS

1. There is a natural environment that can be preserved on the subject reach of Milk Creek. The finding of a natural environment is based upon fish, macroinvertebrate, and habitat surveys conducted by Colorado Parks and Wildlife ("CPW") and BLM. The natural environment:

> **a)** includes native and introduced fishes, aquatic macroinvertebrates, and riparian communities. The natural environment supports roundtail chub, flannelmouth sucker, and bluehead sucker, which appear on BLM's sensitive species list. The natural environment supports a healthy community of mayfly, stonefly, and caddisfly taxa. The natural environment supports riparian communities and species, including willow species, cottonwood species, sedges, and rushes.
> **b)** includes important spawning and rearing habitat for flannelmouth sucker and bluehead sucker during spring and early summer for fish that are seeking ideal habitat to complete their lifecycle. The creek also provides important seasonal spawning habitat for individuals of these species that spend most of their life cycle in the Yampa River. Flannelmouth sucker and bluehead sucker are indicator

species for other elements of the natural environment that rely upon a hydrograph with somewhat natural shape.
c) will be preserved to a reasonable degree with the proposed ISF water right, and
d) can exist without material injury to existing water rights, including conditional surface water rights and conditional storage rights.

2. The instream flow location, amount and timing originally recommended by the CWCB staff at the March 2025 board meeting:

- **a)** is based upon standard field, office, and modeling procedures that are used to identify flow rates necessary to support water-dependent natural resource values. The standard procedures include collecting hydraulic and biologic data, surveying stream channel geometry, and modeling instream hydraulic parameters.
- **b)** is based upon an accurate Systems for Environmental Flow Analysis (SEFA), which is a scientific methodology for identifying the amount of physical habitat available for fish at various flow rates in a specified stream channel, and reflects standard procedures used following the Instream Flow Incremental Methodology (IFIM) approach that is applied nationwide for identifying flow rates needed to support aquatic species and their habitat.
- **c)** is based upon a set of habitat suitability criteria that are appropriate for the fish species and the life stages to be protected.
- **d)** is based upon a set of habitat suitability criteria that are appropriate for the Milk Creek stream channel.
- **e)** is based upon a reasonable selection of protective flow rates taken from the area weighted suitability curves produced by the SEFA analysis in two separate reaches representative of the subject reach of Milk Creek.
- **f)** are required to preserve the natural environment to a reasonable degree, given the habitat needs, fish passage needs, life histories, population composition, and conservation status of the species found in this stream reach.

3. The water availability analysis conducted by the CWCB in support of the March 2025 instream flow appropriation:

- **a)** is based upon scientifically accepted hydrologic analysis procedures.
- **b)** relies upon data from a temporary gage site installed on Milk Creek and operated from July 2017 to December 2024, which demonstrates that sufficient water is available for the proposed appropriation.
- **c)** reflects the amount of water that is available for appropriation as an ISF right, utilizing standard procedures employed by the CWCB. This analysis includes a range of hydrologic year types.
- **d)** reveals that the proposed instream flow water right will not appropriate all available water for instream use but instead leaves a sizable volume of water available for future use and development.

4. BLM supports the CWCB staff recommendations as set forth in the March 2025 Staff Report and Recommendation on the subject reach of Milk Creek.

5. BLM hereby adopts the factual claims set forth in the CWCB staff's Prehearing Statement.

B. LEGAL CLAIMS

1. BLM is a party to these proceedings pursuant to Rule 5l (4) of the ISF Rules.

2. Because ISF water rights are nonconsumptive and do not divert water from the stream, the CWCB can appropriate an ISF right for water that will be diverted downstream by a senior water right.

3. Even though the proposed ISF will be junior to existing water rights on the stream system, the CWCB can make appropriations based on water availability at the time of the proposed appropriation, without subtracting flow rates or volumes that have been adjudicated to conditional or presently unexercised water rights.

4. The proposed ISF water right will not deprive the people of the State of Colorado of their right to develop the volume of water allocated to the State of Colorado under the Colorado River Compact. The proposed ISF water right leaves substantial water volume available for new junior water rights and future water development.

5. In determining the amount of water available for an ISF appropriation, the CWCB is not limited to the amount of water available during drought years.

6. The CWCB has the exclusive authority to determine the amount and timing of water necessary to preserve the natural environment to a reasonable degree.

7. The original CWCB staff ISF recommendation for the subject reach of Milk Creek meets all substantive and procedural requirements outlined in the ISF Rules.

8. The CWCB's appropriation of an instream flow water right on the subject reach of Milk Creek would further the express intent of Section 37-92-103(3), C.R.S. to "correlate the activities of mankind with some reasonable preservation of the natural environment."

9. The proposed ISF right will further develop the ongoing cooperative effort between the BLM and CPW to manage Milk Creek and the Yampa River for sensitive species, furthering the objectives of the Range-Wide Conservation Agreement and Strategy for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker, dated September 2006 and revised in 2019.

10. An instream flow water right held by the Colorado Water Conservation Board, combined with land use protections implemented by the BLM, will provide an optimal management foundation for the continued existence of fish and riparian species in this reach of Milk Creek.

11. BLM hereby adopts the legal claims set forth in the CWCB staff's Prehearing Statement.

C. EXHIBITS TO BE INTRODUCED AT HEARING

1. March 2025 Staff Analysis and Recommendation on the subject reach of Milk Creek. This report, along with its appendices, contains maps of the proposed reach, proposed ISF amounts and timing, and water availability calculations. In the hearing, BLM will refer to this report and its appendices as **Exhibit 1**.

2. Recommendation letter from BLM along with supporting field data, photographs, maps, and water availability analysis. In the hearing, BLM will refer to this report and its appendices as **Exhibit 2**.

3. Recommendation letter from CPW. In the hearing, BLM will refer to this report and its appendices as **Exhibit 3**.

4. Range-Wide Conservation Agreement and Strategy for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker, September 2006. In the hearing, BLM will refer to this report and its appendices as **Exhibit 4**.

5. Final Milk Creek Instream Flow Study Report, prepared by William J. Miller, PhD, Freshwater Consulting, LLC dated September 30, 2024. In the hearing, BLM will refer to this report and its appendices as **Exhibit 5**.

6. Milk Creek Habitat Suitability Criteria for Flannelmouth Sucker and Bluehead Sucker for use in Milk Creek Instream Flow Study by William J. Miller, PhD, Freshwater Consulting, LLC dated January 26, 2024. In the hearing, BLM will refer to this report and its appendices as **Exhibit 6**.

7. I. Jowett, T. Payne, R. Milhouse, 2023. SEFA System for Environmental Flow Analysis Software Manual, version 1.9. BLM will refer to this report as **Exhibit 7.**

8. BLM may introduce demonstrative, rebuttal, or other exhibits as allowed by the CWCB or agreed upon by the Parties.

9. BLM hereby adopts all Exhibits listed in the CWCB staff's Prehearing Statement.

10. BLM may rely upon exhibits introduced or disclosed by any other party to this hearing.

D. WITNESSES

The following witnesses may testify at the hearing as described below, may give rebuttal testimony, and may be available at the hearing to answer questions from the CWCB.

1. Roy Smith, water rights and instream flow coordinator for the BLM (resume available upon request). Mr. Smith may testify about data collection methods, selection of data collection sites, morphological characteristics of Milk Creek, SEFA modeling efforts, how the BLM formulates ISF recommendations, and specifically how he worked with CPW to formulate the BLM's recommendation for the subject reach of Milk Creek.

2. Eric Scherff, BLM hydrologist for the Little Snake Field Office (resume available upon request). Mr. Scherff may testify about the hydrologic and hydraulic characteristics of the subject reach of Milk Creek. In addition, Mr. Scherff may testify regarding channel morphology and the riparian community characteristics of Milk Creek.

3. Tom Fresques, BLM Colorado fisheries biologist (resume available upon request). Mr. Fresques may testify concerning the fishery composition of Milk Creek, the habitat characteristics of Milk Creek, life history and habitat needs of the various fish species found in Milk Creek, fish stocking efforts on Milk Creek, and data collection methods for BLM and CPW fishery surveys completed on Milk Creek.

4. The BLM may call any witness declared by any other party to this hearing.

E. WRITTEN TESTIMONY

BLM does not seek to enter any written testimony at this time. BLM hereby adopts any written testimony listed in the CWCB staff's Prehearing Statement.

F. LEGAL MEMORANDA

BLM does not seek to enter any legal memoranda at this time. BLM hereby adopts any legal memoranda listed in the CWCB staff's Prehearing Statement.

Respectfully submitted this 3rd day of September 2025.

ROY SMITH Digitally signed by ROY SMITH Date: 2025.09.03 07:03:38 -06'00'

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Milk Creek Executive Summary

CWCB STAFF INSTREAM FLOW RECOMMENDATION
March 18-19, 2025

UPPER TERMINUS:	confluence with Wilson Creek at UTM North: 4470717.77	 UTM East: 265448.43
LOWER TERMINUS:	confluence with Yampa River at UTM North: 4475273.74	 UTM East: 265917.99
WATER DIVISION/DISTRICT:	6/44	
COUNTY:	Moffat	
WATERSHED:	Lower Yampa	
CWCB ID:	18/6/A-002	
RECOMMENDER:	Bureau of Land Management (BLM), Colorado Parks & Wildlife (CPW)	
LENGTH:	4.1 miles	
FLOW RECOMMENDATION:	7.8 cfs (01/01 - 02/29) 18 cfs (03/01 - 03/31) 40 cfs (04/01 - 06/30) 8.0 cfs (07/01 - 07/31) 4.5 cfs (08/01 - 09/30) 5.2 cfs (10/01 - 12/31)	

COLORADO
Colorado Water
Conservation Board
Department of Natural Resources

BACKGROUND

Colorado's General Assembly created the Instream Flow and Natural Lake Level Program in 1973, recognizing "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 Colorado Water Conservation Board (CWCB or Board) with the exclusive authority to appropriate and acquire instream flow (ISF) and natural lake level (NLL) water rights. Before initiating a water right filing, the Board must determine that: 1) there is a natural environment that can be preserved to a reasonable degree with the Board's water right if granted, 2) the natural environment will be preserved to a reasonable degree by the water available for the appropriation to be made, and 3) such environment can exist without material injury to water rights.

The information contained in this Executive Summary and the associated supporting data and analyses form the basis for staff's ISF recommendation to be considered by the Board. This Executive Summary provides sufficient information to support the CWCB findings required by ISF Rule 5i on natural environment, water availability, and material injury. Additional supporting information is located at: https://cwcb.colorado.gov/2024-isf-recommendations.

RECOMMENDED ISF REACH

BLM recommended that the CWCB appropriate an ISF water right on a reach of Milk Creek at the ISF Workshop in January, 2017. CPW became a co-recommender for Milk Creek in 2023. Milk Creek is located within Moffat County and is approximately 14 miles southwest from the City of Craig, CO (See Vicinity Map). The stream originates near the Sleepy Cat Peak and flows northwest and north until it reaches the confluence with the Yampa River. The proposed ISF reach extends from the confluence with Wilson Creek downstream to the confluence with the Yampa River for a total of 4.1 miles. Sixy-one percent of the land on the proposed reach is BLM property and the remaining 39% is privately owned (See Land Ownership Map).

Agency Goals

BLM and CPW are interested in protecting Milk Creek because it provides known spawning and rearing habitat for native Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub (known as the Three Species). The Three Species are large-bodied native fishes endemic to rivers and streams of western Colorado. The Three Species are exhibiting a downward trend and collectively occupy less than half of their native range in the Colorado River Basin (Bezzerides and Bestgen, 2002). The importance of this reach of Milk Creek for native fishes led to cooperation between the BLM and CPW to document use by native species, implement fish stocking programs, and complete cooperative studies to determine the flow rates needed to support the natural environment.

CPW is a signatory, along with the BLM, other federal agencies, and multiple tribes to the Range-Wide Conservation Agreement and Conservation Strategy for the Three Species (UDWR, 2019). The goal of the Conservation Strategy is to ensure the persistence of populations of the Three Species throughout their respective ranges. CPW and BLM seek to reduce the imperiled status of these species across their historic range in Colorado in order to protect the species and to reduce the risk of a federal listing as threatened or endangered under the Endangered Species Act (ESA). Factors contributing to their decline include hydrologic alteration, lack of connectivity, and predation by and hybridization with non-native species.

CPW and BLM have dedicated significant resources to bolstering these populations through non-native fish control, reservoir screening projects, research on movement patterns and spawning behavior in tributaries like Milk Creek, and supplemental stocking to augment populations. From 2015 to 2024, CPW has proactively stocked over 20,000 Bluehead Sucker and over 3,500 Flannelmouth Sucker in Milk Creek to bolster populations in both Milk Creek and the Yampa River. This effort was the first of its kind to stock small numbers of Bluehead and Flannelmouth Suckers with the goal of augmenting the Milk Creek population and hopefully reestablishing populations of these species throughout the Yampa River basin via dispersal from Milk Creek. By boosting populations in unique tributary environments like Milk Creek, additional populations may also become established in the Yampa River mainstem where non-natives are suppressed by non-native fish control efforts. In addition, CPW tags stocked native fish with Passive Integrated Transponders, also known as PIT tags, to track annual movement patterns throughout the Upper Colorado River Basin, as well as growth rates.

Milk Creek provides unique habitat characteristics such as sporadic high-flow events, appropriate water temperature, suitable geomorphology, and high turbidity that support native fish populations. Protecting flows in a unique tributary environment like Milk Creek is complementary to other agency actions. Both CPW and BLM believe working with the CWCB to secure an ISF water right is an appropriate tool for protecting streamflows that are critically important for the persistence of the Three Species.

OUTREACH

Stakeholder input is a valued part of the CWCB staff's analysis of ISF recommendations. Currently, more than 1,100 people subscribe to the ISF mailing list. Notice of the potential appropriation of an ISF water right on Milk Creek was sent to the mailing list in November 2024, March 2024, March 2023, March 2022, March 2021, March 2020, March 2019, March 2018, and March 2017. A public notice about this recommendation was also published in the Craig Press on 12/11/2024. Staff spoke with former District 44 Water Commissioner, Kathy Bower, on 05/17/2017 regarding water availability and water rights on Milk Creek. CWCB staff also talked with Sarah Myer on 4/6/2023 when she was the District 44 Water Commissioner about water rights and water administration.

Staff presented information about the ISF program and this recommendation to the Moffat County Board of County Commissioners and the Moffat County Land Board on 8/14/2017 where members of the public as well as representatives of Tri-State Generation and Transmission Association (Tri-State) were also in attendance. Staff discussed this recommendation with the Moffat County Land Use Board again on 9/10/2024. Staff also worked extensively with representatives of Tri-State to inform them about the proposal, update them on studies, and tour the proposed reach on 04/20/2022 and 06/09/2023. Staff discussed the proposed ISF on Milk Creek with Colorado River Water Conservation District staff on 1/6/2024; their staff followed up with local landowners and no issues were raised.

NATURAL ENVIRONMENT

CWCB staff relies on the recommending entity to provide information about the natural environment. In addition, staff reviews information and conducts site visits for each recommended ISF appropriation. This information provides the Board with a basis for determining that a natural environment exists.

Physical Habitat

Milk Creek is the largest tributary to the Yampa River between the confluence of the Williams Fork and Little Snake Rivers. The proposed reach on Milk Creek is a low to moderate gradient stream in a canyon approximately 0.5 miles in width. In some locations, there is sufficient width in the canyon bottom for the stream to meander over time. In other locations, stream movement is confined by bedrock. The creek has a stable channel but has a highly variable substrate size, including fine sediment, gravels, and large 2-foot diameter boulders. The stream has a good mix of riffle, run, and pool habitat to support native fish populations. Water quality, water temperatures, and food sources are also suitable for native species.

Native Fishery

Fishery surveys indicate that the lowest 4.1 miles of Milk Creek provides habitat for native species, including Flannelmouth Sucker *(Catostomus latipinnis)*, Bluehead Sucker (*Catostomus discobolus*), Roundtail Chub (*Gila robusta*), and Speckled Dace (*Rhinichthys osculus*), see Table 1. The Three Species 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 Three Species meet the first two of the criteria listed above, qualifying them as BLM "sensitive species" (BLM, 2025). The Three Species are also listed in the Colorado State Wildlife Action Plan (2015) as Tier 1 Species of Greatest Conservation Need, or "species which are truly of highest conservation priority in the state."

Table 1. List of native fish species identified in Milk Creek.

Species Name	Scientific Name	Status
flannelmouth sucker	*Catostomus latipinnis*	State - Species of Greatest Conservation Need BLM – Sensitive Species
bluehead sucker	*Catostomus discobolus*	State - Species of Greatest Conservation Need BLM – Sensitive Species
roundtail chub	*Gila robusta*	State - Species of Greatest Conservation Needn BLM – Sensitive Species
speckled dace	*Rhinichthys osculus*	None

As a significant low elevation perennial tributary to the Yampa River, Milk Creek provides important year-round and seasonal habitat for the Three Species. Very few similar tributaries enter the Yampa River in this area, so it is critical for restoring native fish populations in the Yampa River watershed. Tributary habitats provide unique refugia for juvenile native fish where threats of predation and hybridization with non-native species may be substantially lower than those in the mainstem Yampa River.

Based on CPW data, there is heavy use by adult Three Species during the spring high-flow period and receding limb, specifically Bluehead Sucker and Flannelmouth Sucker. Flannelmouth Suckers and Bluehead Suckers have been known to travel long distances toward habitual spawning areas. During the rising limb of the hydrograph when the water temperature reaches approximately 13°C, Flannelmouth Sucker migrate into tributaries to spawn. Bluehead Suckers follow shortly after, once water temperature reaches 16°C. In Milk Creek this window typically occurs between April to mid-May annually but can vary significantly from year-to-year. Roundtail Chub can be found in Milk Creek and its tributary Stinking Gulch, but their densities are low near the Yampa River confluence. This is likely driven by low densities of Roundtail Chub in the Yampa River. Most of the Roundtail Chub in lower Milk Creek are juveniles. Roundtail Chub of all life stages are present higher in the drainage above Axial Basin. For additional information about fish movement patterns and research in Milk Creek please see CPW's recommendation letter and attached report.

Nonnative Fishery
Non-native fish species that utilize Milk Creek include Black Bullhead (*Ameiurus melas*), Brook Stickleback (*Culaea inconstans*), Brown Trout (*Salmo trutta*), Common Carp (*Cyprinus carpio*), Creek Chub (*Semotilus atromaculatus*), Fathead Minnow (*Pimephales promelas*), Green Sunfish (*Lepomis cyanellus*), Iowa Darter (*Etheostoma exile*), Northern Plains Killifish (*Fundulus kansae*), Red Shiner (*Cyprinella lutrensis*), Sand Shiner (*Miniellus stramineus*), Smallmouth Bass (*Micropterus dolomieu*), White Sucker (*Catostomus commersonii*), White x Bluehead Sucker Hybrid, and White x Flannelmouth Sucker Hybrid.

Macroinvertebrate Community
Aquatic macroinvertebrates are an important component of aquatic food webs and serve as an important food source for fish. In October 2023, CPW staff collected macroinvertebrate samples at two sites within the proposed ISF reach. Analysis of the macroinvertebrate data results show both sites are attaining and meeting the state standards for macroinvertebrate health and biodiversity. Other metrics indicate that Milk Creek has relatively few pollution tolerant species. Both sites also had a high number of unique species demonstrating a community that is species rich with relatively high biodiversity. Additional details on the macroinvertebrate sampling and results are available in CPW's recommendation letter.

Riparian Community
Milk Creek supports a riparian community comprised primarily of willows, sedges, cottonwoods, and rushes. The riparian community has been impacted by historical grazing practices but is now on an upward trend in lower portions of the reach and is static farther upstream. This reach also hosts mature cottonwood trees and substantial cottonwood regeneration has been observed.

ISF QUANTIFICATION
CWCB staff relies on the biological expertise of the recommending entity to quantify the amount of water required to preserve the natural environment to a reasonable degree. CWCB staff performs a thorough review of the quantification analyses completed by the recommending entity to ensure consistency with accepted standards.

Quantification Methodology

Instream Flow Incremental Methodology (IFIM) using System for Environmental Flow Analysis (SEFA)

CPW and BLM utilized professional judgement and past experiences to determine the appropriate methodology for the Milk Creek ISF recommendation. The BLM and CPW decided to use a methodology that is species-specific and can be tailored to assessing flow and habitat relationships specific to Flannelmouth Sucker and Bluehead Sucker. BLM and CPW used IFIM, a widely accepted method for quantifying suitable hydraulic habitat as a function of discharge for specific species and life stages of fish. In 2023, CWCB hired Bill Miller to provide field support and technical training necessary to complete a hydraulic habitat model on Milk Creek using SEFA. The SEFA software is a modern version of the Physical Habitat Simulation software (PHABSIM), a program which was historically used for all of Colorado's ISF evaluations using the IFIM framework. As legacy software, PHABSIM was not updated for compatibility to Windows Operating System 11. The SEFA software is the modern equivalent with additional features, one of which is the predicting fish passage across transects. Bill Miller trained BLM, CPW, and CWCB staff in field methods and use of the SEFA software, developed the models, and completed a summary report (Miller, 2024a).

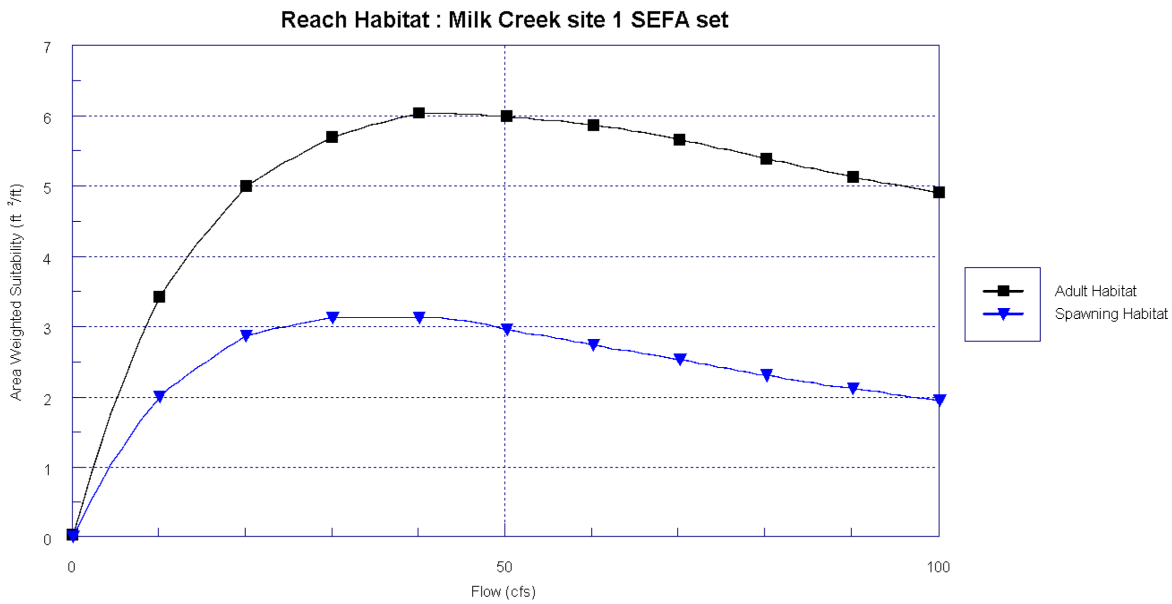
Habitat Suitability Criteria (HSC)

HSC represent a fish species' preference for habitat variables such as depth, velocity, substrate, or cover. For this ISF evaluation, HSC for adult Flannelmouth Sucker and Bluehead Sucker were updated in early 2024 (Miller, 2024b). A combination of data was used including radio telemetry studies on the Colorado River near Grand Junction, existing occupancy data from a range of rivers, and a literature review of habitat and population studies. There is relatively limited habitat suitability data specific to Bluehead Sucker, so HSC for Flannelmouth Sucker were used as a surrogate. Bluehead Sucker have different feeding preferences than Flannelmouth Sucker and are known to feed by scraping algae and periphyton from cobble-sized substrates in faster riffle habitats. Flannelmouth Sucker tend to feed on aquatic invertebrates and detritus found in finer substrates in habitats with relatively low velocities. Given these differences, the habitat response shown for Flannelmouth Sucker approximates habitat response to flow for Bluehead Sucker but will not fully depict all areas suitable for Bluehead Sucker. The suitability indices used in the hydraulic-habitat modeling are a combination of the data from Flannelmouth Sucker and Bluehead Sucker studies on the Colorado River and literature from the U.S. Fish and Wildlife Service (Miller, 2024b).

Flannelmouth Sucker and Bluehead Sucker spawn in riffle habitat over gravel and cobble substrate. Spawning habitat use is generally restricted to shallower depths and higher velocity than the broader habitat types used by adults. The spawning HSC for both species were based on a combination of literature review and existing habitat suitability criteria from the U.S. Fish and Wildlife Service (Miller, 2024b). Suitable spawning substrate material was restricted to gravel and cobble substrate types in the model to accurately reflect the use of these sites during spawning.

Data Collection and Analysis
In fall of 2023, Bill Miller, BLM, CPW, and CWCB staff performed site selection and field data collection to build a hydraulic habitat model for the Milk Creek ISF reach in SEFA. After assessing the four-mile ISF reach, a study area was selected that is representative of the ISF reach. Two study sites were surveyed on BLM lands – Site 1 was approximately 0.5 miles above the confluence with the Yampa River and Site 2 was approximately 0.9 miles above the confluence. The two study sites include a variety of riffle, run and pool habitat types with bed substrate that ranges in size from fine silt to large cobble. Surveys were conducted in October 2023 to establish bed topography. An initial hydraulic habitat-discharge relationship was analyzed under baseflow conditions (approximately 6 cfs). In spring 2024, two additional sets of measurements were made to calibrate the model over a range of flows, these include measurements at a mid-flow (approximately 45-50 cfs in April) and a high flow (approximately 127 cfs in June). Streamflow and habitat were modeled from 5 cfs to 300 cfs.

In SEFA, the amount of suitable habitat computed at various flow rates is referred to as Area Weighted Suitability (AWS). The AWS is the Combined Suitability Index (CSI) for depth, velocity and substrate for each measurement point weighted by the area the point represents. Results for combined AWS for depth, velocity, and substrate are shown below for the two study areas (Figure 1).



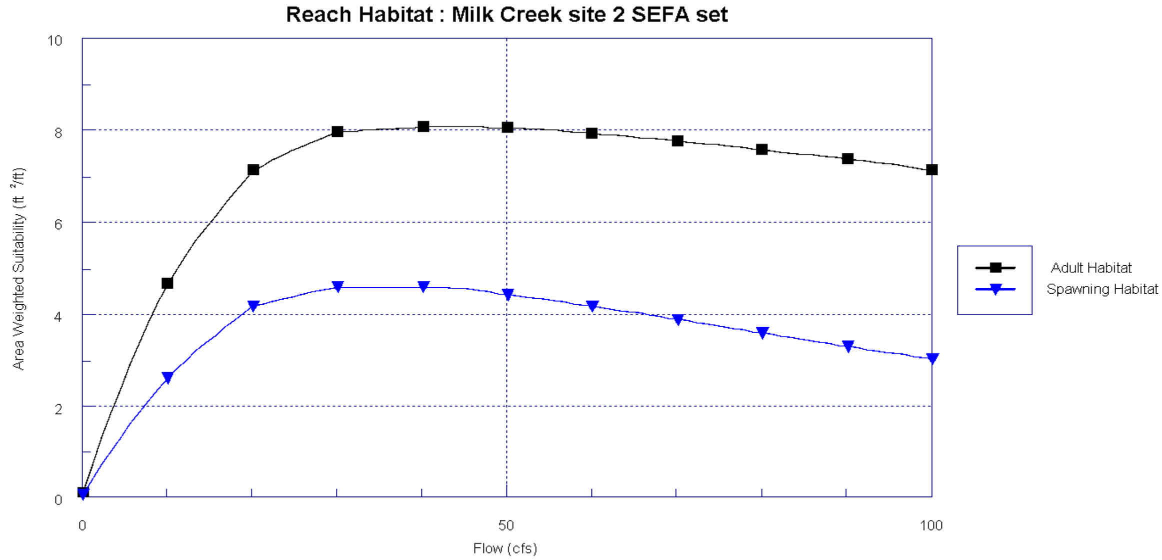


Figure 1. Hydraulic Habitat Modeling Results Graphs for site 1 (top) and site 2 (bottom)

The hydraulic habitat modeling results for both sites were comparable with maximum AWS for occurring at a flow of 40 cfs for adult sucker species. For spawning habitat, the maximum AWS occurs from 30 cfs to 40 cfs for both sites. For both general adult habitat and spawning habitat, AWS decreases rapidly below 40 cfs, indicating that additional increments of discharge provide significant habitat response benefits as flows approach 40 cfs. At flows greater than 40 cfs, additional increments of discharge provide smaller habitat benefits.

Fish Passage

Longitudinal connectivity is important in riverine systems to allow migration and localized movement required by fish and other aquatic biota. Flannelmouth Sucker and Bluehead Sucker migrate from larger rivers into smaller tributary streams such as Milk Creek for spawning, and habitat connectivity is critical for that life stage. Analysis of fish passage is one means to assess connectivity and evaluate the flows needed to allow fish migration.

A fish passage assessment was conducted using a depth criteria of 0.6 feet (7 inches). This was chosen based on professional judgment as this depth is approximately double the body depth of an adult Flannelmouth Sucker. This is protective of Bluehead Sucker because Flannelmouth Sucker is the larger of the two species. The SEFA fish passage connectivity evaluation showed that at a flow of 8.0 cfs, all cross-sections measured show a continuous pathway for fish passage that is at least 2 feet in width and at least 0.6 feet in depth at both study sites.

ISF Recommendation

Using the approach and results summarized above, biological expertise, and staff's water availability analysis, CPW and BLM developed the following instream flow recommendations.

7.8 cfs – January 1 through February 29
This recommended flow rate is based on limited water availability during the baseflow period. This flow rate will provide conditions to enable longitudinal movement of resident fish to find more advantageous habitat.

18.0 cfs - March 1 through March 31
A flow rate of 18 cfs will provide enabling conditions during the beginning of the spawning period for native fish, a critical period for completing their life cycle. As low elevation snowmelt runoff begins in the early part of spring, it is important to preserve flows that begin to cue native fish and allow longitudinal movement between habitat types in order to reach suitable spawning areas.

40.0 cfs – April 1 through June 30
A flow rate of 40 cfs supports preferred habitat for adult Bluehead and Flannelmouth Sucker across both sites. This flow rate also supports preferred spawning habitat for these species. Preserving this flow rate during the spring runoff period (including the rising and receding limb of the hydrograph) will support native fish by providing optimal depth, velocity, and substrate conditions to enable spawning migrations, as well as optimal overall habitat conditions for adult species. The snowmelt runoff peak can occur anytime between April and June on Milk Creek and is critically important in cueing native fish species to spawn, as well as providing geomorphic functions that support life cycle requirements of these fish. The higher flow rate supports sediment mobilization in the stream which supports habitat diversity and healthy spawning beds by flushing fines from interstices to support clean cobble and gravel substrate in the channel (the preferred spawning substrate for these species). Higher flows also support recruitment of woody debris and organic materials that can facilitate healthy stream function as well as a robust macroinvertebrate food base for fish. Protecting this flow rate over this extended spring runoff time period will provide a ramp during and after peak flows that helps with drift, dispersal, and incubation of eggs in the channel.

8.0 cfs - July 1 through July 31
The SEFA fish passage evaluation showed that 8 cfs will preserve a pathway for fish that is at least 2 feet wide and 0.6 feet deep across all modeled cross-sections at both study sites. The recommended flow rate (8 cfs) will maintain longitudinal connectivity of habitat and will enable large-bodied adult fish to move throughout Milk Creek to find suitable habitat or to emigrate into the Yampa River without being stranded. Additionally, this flow rate will support larvae development and emergence by maintaining wetted area in the channel and channel margins. This flow rate will support both fish passage for all life stages of native fish and habitat for larvae development and young-of-the-year fish to grow and mature in channel margins, creating refuge habitat for larvae, young-of-the-year, and juvenile fish.

4.5 cfs – August 1 through September 30
This recommended flow rate is based on limited water availability during the late irrigation season. Despite low flow conditions and limited mobility between habitat types, native species will use available habitat within Milk Creek during this period. Preserving this flow rate is important because it enables rearing of juvenile and young-of-the-year fish. Growth during this late summer period is critical to their survival over the winter period. There is reduced occupancy by non-native species and less competition foraging in Milk Creek than in the mainstem Yampa River.

5.2 cfs – October 1 through December 31
This recommended flow rate is based on limited water availability during the baseflow period. Baseflow during the winter months is necessary to provide enough habitat variety to overwinter resident native fish.

WATER AVAILABILITY

CWCB staff conducts hydrologic analyses for each recommended ISF appropriation to provide the Board with a basis for determining that water is available.

Water Availability Methodology

Each recommended ISF reach has a unique flow regime that depends on variables such as the timing, magnitude, and location of water inputs (such as rain, snow, and snowmelt) and water losses (such as diversions, reservoirs, evaporation and transpiration, groundwater recharge, etc.). This approach focuses on streamflow and the influence of flow alterations, such as diversions, to understand how much water is physically available in the recommended reach.

Staff's hydrologic analysis is data-driven, meaning that staff gathers and evaluates the best available data and uses the best available analysis method for that data. Whenever possible, long-term stream gage data (period of record 20 or more years) are used to evaluate streamflow. Other streamflow information such as short-term gages, temporary gages, spot streamflow measurements, diversion records, and regression-based models are used when long-term gage data is not available. CSUFlow18 is a multiple regression model developed by Colorado State University researchers using streamflow gage data collected between 2001 and 2018 (Eurich et al., 2021). This model estimates mean-monthly streamflow based on drainage basin area, basin terrain variables, and average basin precipitation and snow persistence. Diversion records are used to evaluate the effect of surface water diversions when necessary. Interviews with water commissioners, landowners, and ditch or reservoir operators can provide additional information. A range of analytical techniques may be employed to extend gage records, estimate streamflow in ungaged locations, and estimate the effects of diversions. The goal is to obtain the most detailed and reliable estimate of hydrology using the most efficient analysis technique.

The final product of the hydrologic analysis used to determine water availability is a hydrograph, which shows streamflow and the proposed ISF rate over the course of one year. The hydrograph will show median daily values when daily data is available from gage records; otherwise, it will present mean-monthly streamflow values. Staff will calculate 95% confidence intervals for the median streamflow if there is sufficient data. Statistically, there is 95% confidence that the true value of the median streamflow is located within the confidence interval.

Basin Characteristics

The contributing basin of the proposed ISF on Milk Creek is 223 square miles, with an average elevation of 7,336 feet and average annual precipitation of 21.4 inches. The drainage basin is snowmelt driven. Snowmelt runoff can initiate early relative to other basins due to the generally low elevation of the watershed. Baseflow conditions are low, while runoff can be several orders of magnitude higher.

Water Rights Assessment

There are no active water rights within the proposed reach on Milk Creek. There are a large number of water rights influencing hydrology in the drainage basin upstream. This includes 338 cfs in active direct flow diversions, 2,606 acre-feet in storage, 152 springs totaling 5.9 cfs, and a number of wells. A significant portion of the water rights in the lower portion of the basin are owned by Tri-State which then lease the water rights to farms and ranches. Private ranches and water right owners are generally located higher in the basin. There is one transbasin import, the Highline Ditch (WDID 4400814, 3.3 cfs with a 1897 appropriation date, and 3.0 cfs with a 1914 appropriation date) that brings water to Milk Creek from the basin to the east (diversion point is on Deer Creek which is a tributary to Morapas Creek) which is used to irrigate lands along Stinking Gulch, a tributary of Milk Creek just above the proposed upper terminus. There is also a large conditional right on the Yampa River at the mouth of Milk Creek for a potential pipeline (Yampa River Milk Ck PL WDID 4402029, 400 cfs appropriated in 1975)

Data Collection and Analysis

Representative Gage Analysis

There is not a long-term gage within the proposed reach on Milk Creek. There was a historic gage (USGS 0925000, Milk Creek near Thornburg) which was located about 14 miles upstream from the proposed reach and operated from 1952-1986. This gage was determined not to be suitable to evaluate water availability due to the large percentage of the basin area and water rights located downstream from the gage. There were short-term historic gages on several of the tributaries that join Milk Creek within a few miles of the proposed upper terminus (Jubb Creek near Axial, CO (USGS 09250610, 1975-1981; Morgan Gulch near Axial, CO, USGS 09250700, 1980-1981; Wilson Creek near Axial, CO, USGS 09250600, 1974-1980). Staff explored these datasets but determined that there was insufficient data on enough of the system to understand water availability in the proposed reach.

Due to insufficient representative streamflow data, CWCB staff installed a temporary gage on Milk Creek in July of 2017 (See the Site Map). This gage was subsequently moved a short distance upstream in 2018 and remains in operation. The gage consists of a staff plate, HOBO MX2001 pressure transducer which recorded water level in 15 min intervals, and a camera. There are a number of data gaps due to several high streamflow events that disrupted the gage equipment, equipment failures, and ice affected data.

The CWCB gage record was compared to a nearby climate station to evaluate how the historical record compares to a longer record. The closest climate station was located approximately 14 miles to the northeast at the Craig Airport (USC00024046 Craig Moffat CO Airport). Daily precipitation data was available through CDSS from 4/1/1998 to 7/31/2024 with full years of data missing in 2003, 2007, and 2013 and partial years of data missing in 1998 and 2024. Over the CWCB gage record that could be evaluated (2018-2023), three years had below 25th percentile annual precipitation (2020, 2021, and 2023), two years were just under the median (2018 and 2022), and 2019 was above the 75th percentile. Therefore, the CWCB gage data likely includes a range of low flow conditions and higher flow conditions, but most of the data is duirng years when the precipitation in the area was less than median.

Based on the CWCB gage data, streamflow typically begins to increase in March and recede by late June. Most years of data show peak flows above 50 cfs and in 2019 the instantaneous peak was above 500 cfs. The Milk Creek gage data from 7/14/2024 to 12/19/2024 was used to calculate mean-monthly streamflow. No adjustments were made for the small change in gage location or to extrapolate flow slightly downstream to the lower terminus.

Site Visit Data

CWCB staff made 41 streamflow measurements on the proposed reach of Milk Creek as part of operating the CWCB Milk Creek gage (Table 3).

Table 3. Summary of streamflow measurements for Milk Creek.

Visit Date	Flow (cfs)	Collector
07/13/2017	3.92	CWCB
08/01/2017	4.66	BLM
08/14/2017	2.43	BLM
10/05/2017	14.13	BLM
11/27/2017	9.77	BLM
05/08/2018	170.01	CWCB
06/04/2018	6.63	CWCB
08/15/2018	0.34	BLM
09/13/2018	0.57	CWCB
11/14/2018	3.83	BLM
04/19/2019	105.50	BLM
05/07/2019	263.26	CWCB
07/12/2019	22.08	BLM
07/30/2019	11.33	CWCB
10/08/2019	4.72	BLM
12/05/2019	13.10	CWCB
11/19/2020	6.31	CWCB
04/05/2021	17.13	CWCB
05/13/2021	17.47	CWCB
06/16/2021	1.31	CWCB
07/22/2021	1.24	CWCB
08/19/2021	3.08	CWCB
09/15/2021	1.15	CWCB
11/01/2021	5.11	CWCB

04/20/2022	38.46	BLM, CPW, CWCB
05/24/2022	47.20	CPW, CWCB
08/18/2022	1.82	CWCB
11/01/2022	6.63	CWCB
06/07/2023	146.00	CWCB
07/25/2023	5.73	CWCB
08/16/2023	8.24	CWCB
10/10/2023	4.84	CWCB
10/24/2023	5.72	CPW, CWCB
11/10/2023	4.99	CWCB
03/28/2024	28.21	CWCB
04/12/2024	52.22	CPW
05/29/2024	127.60	CWCB
06/27/2024	13.13	CWCB
08/06/2024	4.37	CWCB
10/09/2024	2.27	CWCB
12/18/2024	5.34	CWCB

Water Availability Summary
The hydrograph shows mean-monthly streamflow for the CWCB Milk Creek gage and the proposed ISF rate (See Complete Hydrograph). The proposed ISF flow rate is below the mean-monthly streamflow. Staff concludes that water is available for appropriation on Milk Creek.

MATERIAL INJURY
If decreed, the proposed ISF on Milk Creek would be a new junior water right. This ISF water right can exist without material injury to other senior water rights. Under the provisions of section 37-92-102(3)(b), C.R.S., the CWCB will recognize any uses or exchanges of water in existence on the date this ISF water right is appropriated.

ADDITIONAL INFORMATION

Common Acronyms and Abbreviations

Term	Definition
af	acre feet
BLM	Bureau of land management
cfs	cubic feet per second
CWCB	Colorado Water Conservation Board
CPW	Colorado Parks and Wildlife
DWR	Division of Water Resources
HCCA	High Country Conservation Advocates
ISF	Instream Flow
NLL	Natural Lake Level
USGS	United States Geological Survey
USFS	United States Forest Service
XS	Cross section

Citations

Bezzerides, N. and K. Bestgen, 2002, Status review of Roundtail Chub, Flannelmouth Sucker, and Bluehead Sucker in the Colorado River Basin. Larval Fish Laboratory, Colorado State University, Fort Collins.

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Colorado Water Conservation Board, 2022, R2Cross model- User's manual and technical guide. Retrieve from URL: https://r2cross.erams.com/

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Ferguson, R.I., 2007. Flow resistance equations for gravel- and boulder-bed streams. Water Resources Research 43. https://doi.org/10.1029/2006WR005422

Ferguson, R.I., 2021. Roughness calibration to improve flow predictions in coarse-bed streams. Water Res 57. https://doi.org/10.1029/2021WR029979

Miller, B., 2024a, Final Milk Creek Instream Flow Study Report, September 30, 2024

Miller, B., 2024b, Proposed Habitat Suitability Criteria for Flannelmouth Sucker and Bluehead Sucker for use in Milk Creek Instream Flow Study, January 26, 2024

Nehring, B.R., 1979, Evaluation of instream flow methods and determination of water quantity needs for streams in the state of Colorado, Colorado Division of Wildlife.

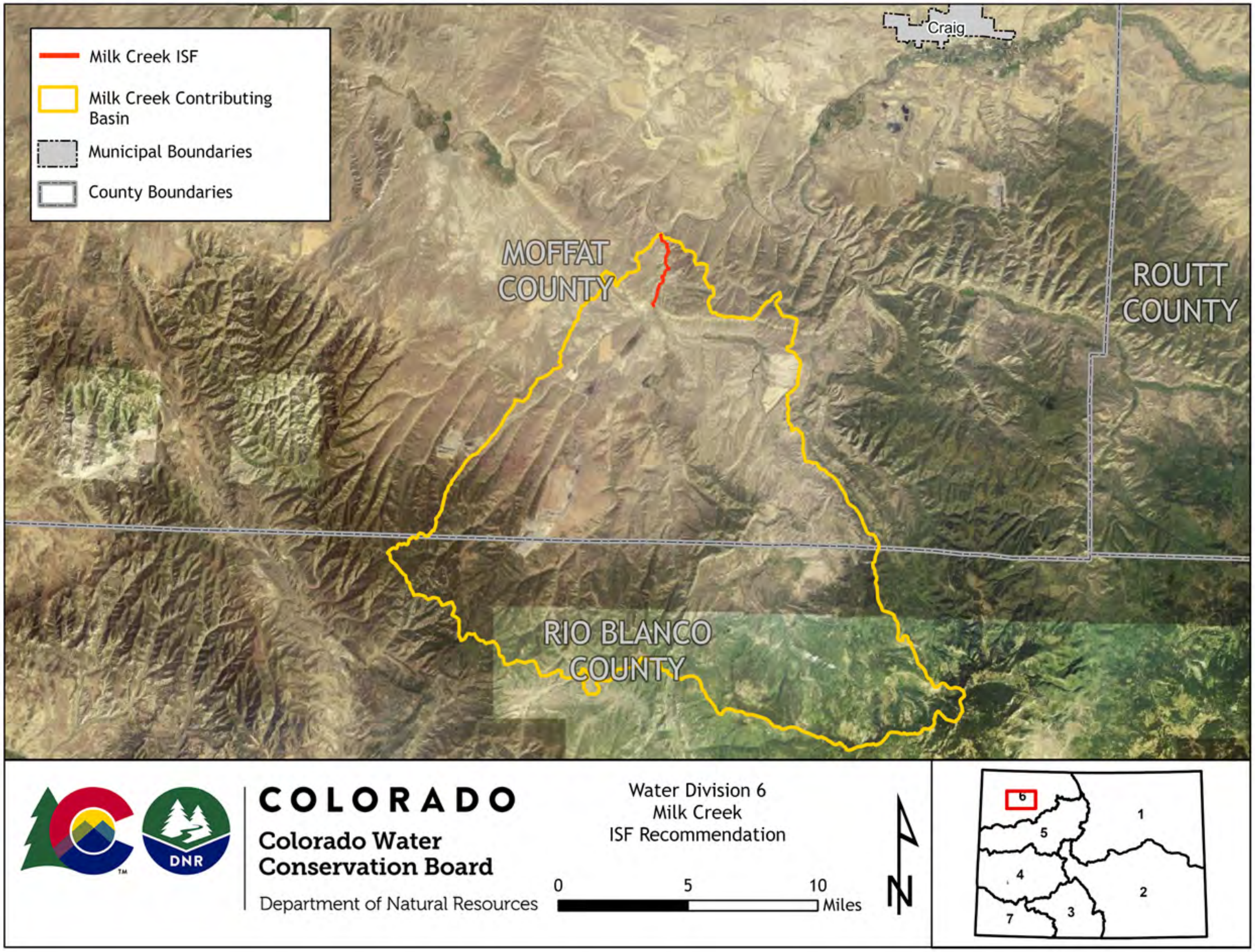
Utah Division of Wildlife Resources (UDWR), 2019, Range-wide conservation agreement and strategy for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker. Publication Number 06-18. Prepared for Colorado River Fish and Wildlife Council. Utah Department of Natural Resources, Division of Wildlife Resources, Salt Lake City, Utah

Metadata Descriptions

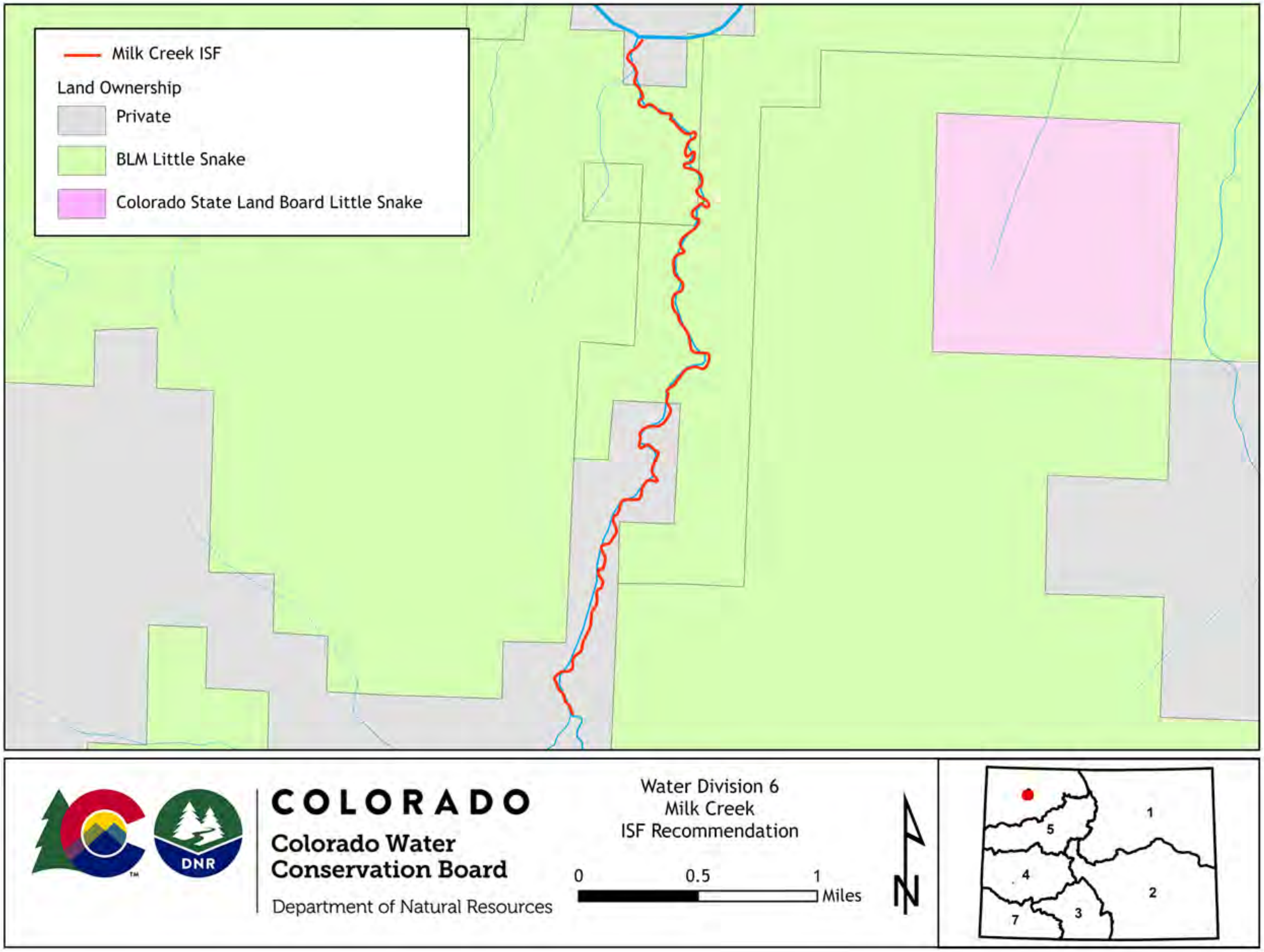
The UTM locations for the upstream and downstream termini were derived from CWCB GIS using the National Hydrography Dataset (NHD).

Projected Coordinate System: NAD 1983 UTM Zone 13N.

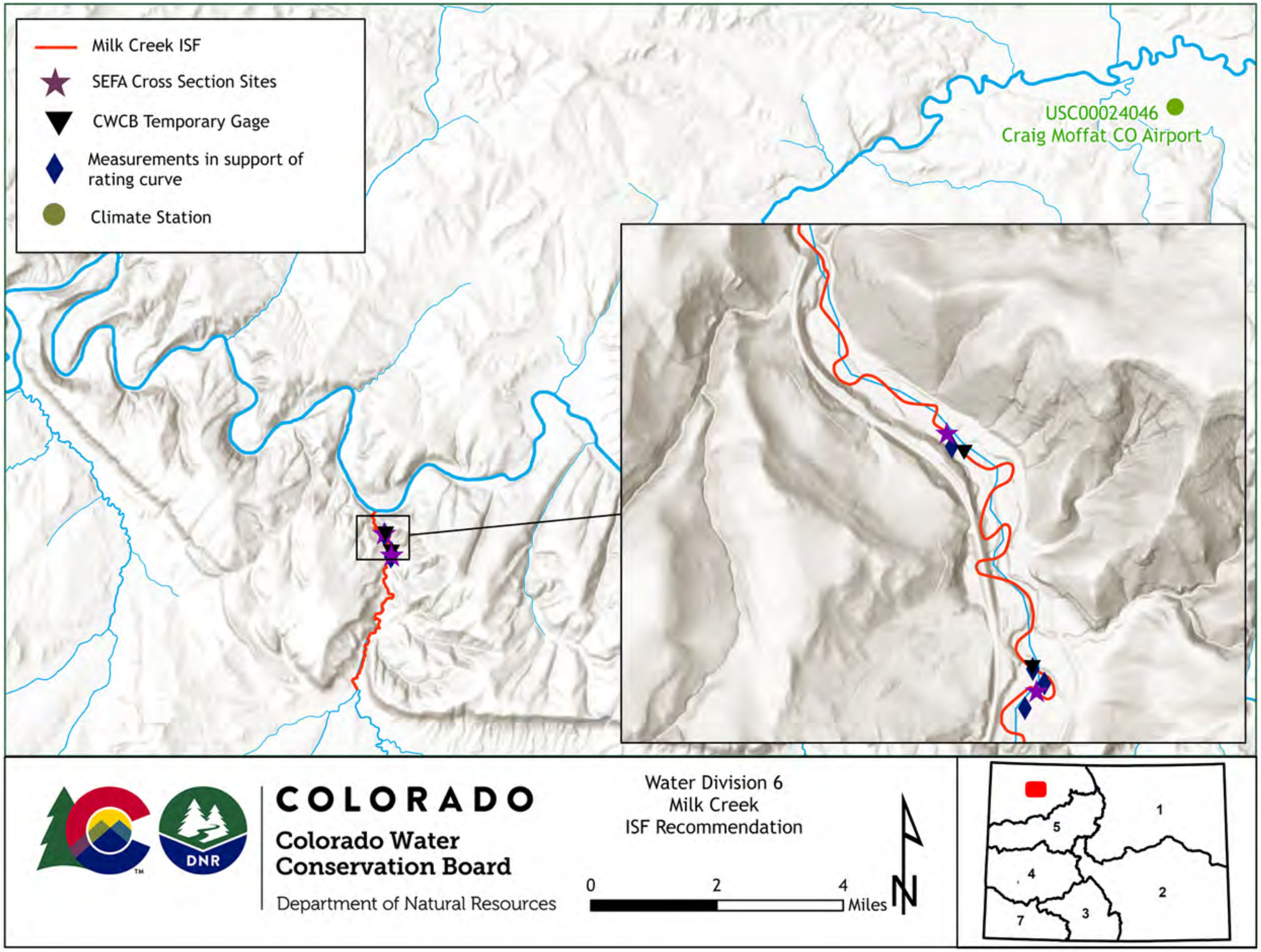
VICINITY MAP



LAND OWNERSHIP MAP



SITE MAP


Milk Creek ISF
SEFA Cross Section Sites
CWCB Temporary Gage
Measurements in support of rating curve
Climate Station
USC00024046
Craig Moffat CO Airport
COLORADO
Colorado Water Conservation Board
Department of Natural Resources
DNR
Water Division 6
Milk Creek
ISF Recommendation
0
2
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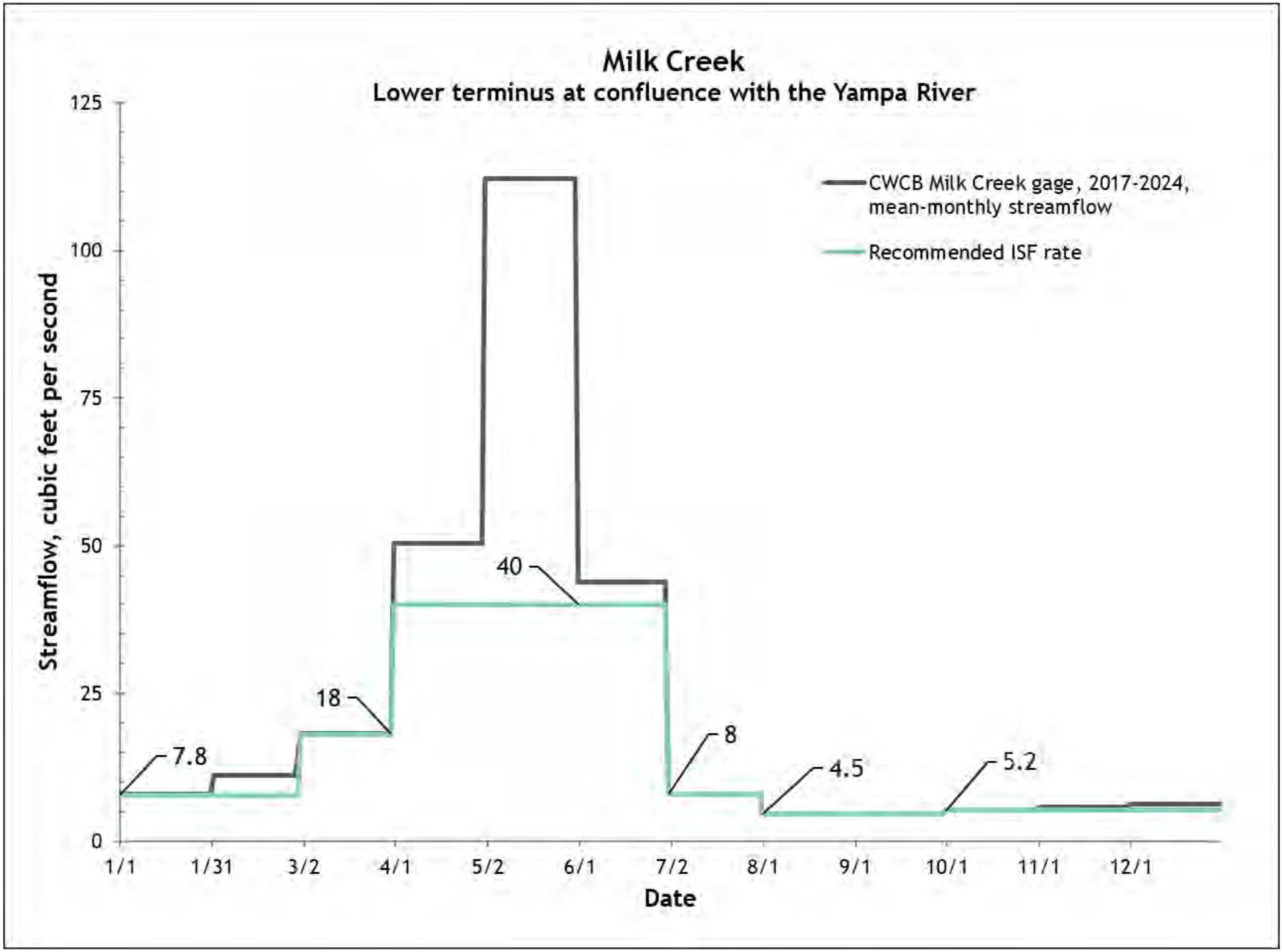
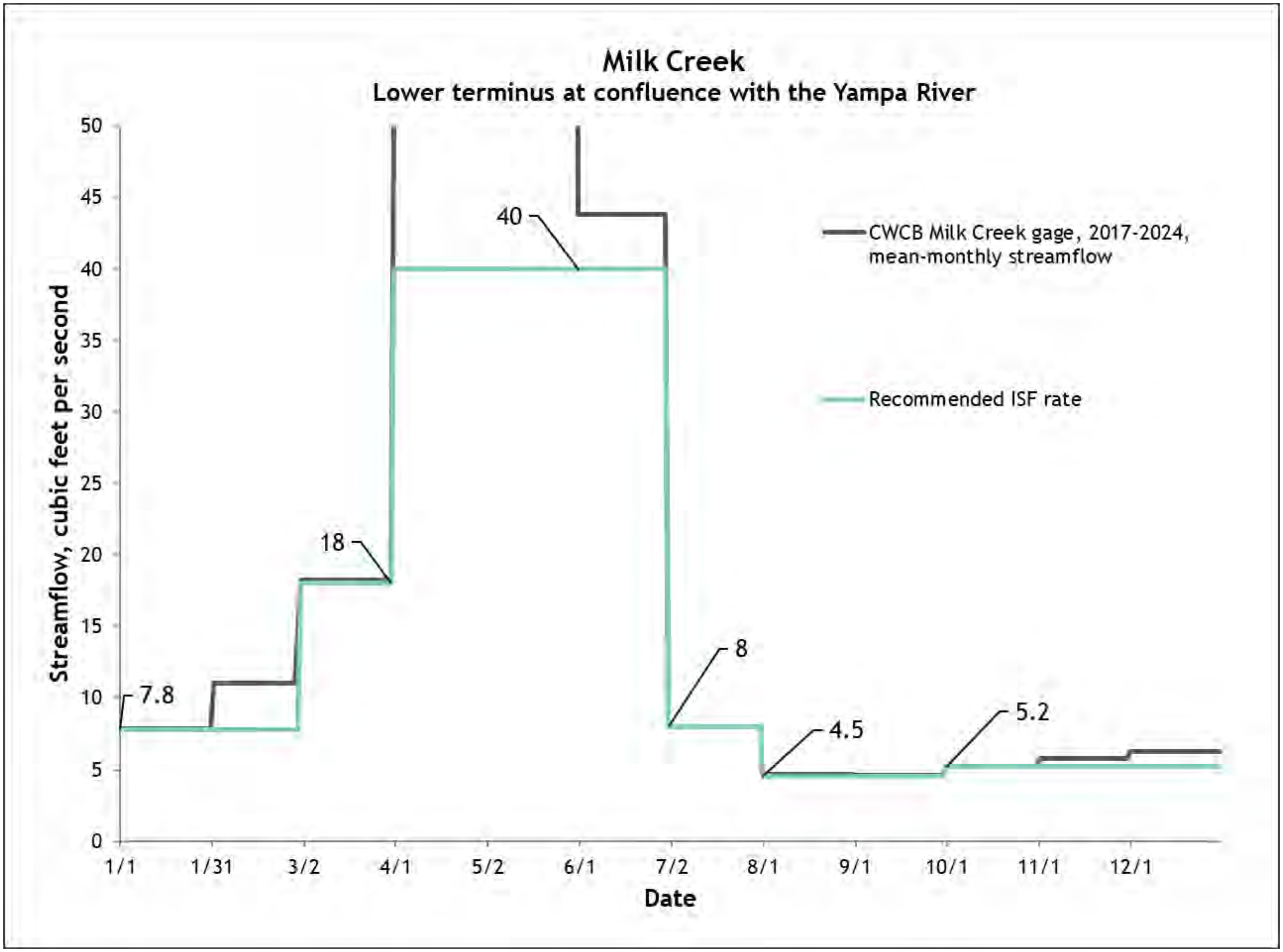
COMPLETE HYDROGRAPH



DETAILED HYDROGRAPH



United States Department of the Interior
BUREAU OF LAND MANAGEMENT

Colorado State Office
Denver Federal Center, Building 40
Lakewood, Colorado 80225
www.blm.gov/colorado

In Reply Refer To:
CO-932 (7250)

Mr. Rob Viehl
Colorado Water Conservation Board
1313 Sherman Street, Room 721
Denver, Colorado 80203

Dear Mr. Viehl:

The Bureau of Land Management (BLM) is writing this letter to formally communicate its instream flow recommendation for lower Milk Creek, located in Water Division 6. Milk Creek is tributary to the Yampa River approximately 12 miles southwest of Craig, Colorado. This recommendation covers the stream reach beginning at the confluence with Wilson Creek and extends downstream to the confluence with the Yampa River, a distance of 4.1 miles. Of this reach, BLM manages 2.49 miles, while 1.62 miles are in private ownership.

The importance of this stream reach for native fishes has led to cooperation between the BLM and Colorado Parks and Wildlife (CPW) to document use by native species, implement fish stocking programs, and complete cooperative studies to determine the flow rates needed to support the natural environment. Milk Creek is known to provide habitat for Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub, large-bodied native fishes endemic to rivers and streams of western Colorado. BLM and CPW are signatories to a multi-state, multi-agency conservation agreement designed to protect and enhance habitat for these species, with the objective of preventing the need to list any of these species under the Endangered Species Act. This agreement is entitled “Range-Wide Conservation Agreement and Strategy for Roundtail Chub (*Gila robusta*), Bluehead Sucker (*Catostomus discobolus*), and Flannelmouth Sucker (*Catostomus latipinnis*).” The agreement was signed in 2006 and is also known as the “Three Species Agreement.” The intention of the agreement is to increase populations and distribution of the identified species, thereby assisting in their long-term persistence.

The success of the Three Species Agreement could potentially curtail the need for federal listing of these species under the Endangered Species Act (ESA). Establishment of instream flow protection for streams known to provide habitat for the species is identified as a priority conservation action under the Three Species Agreement. Appropriation of an instream flow water right is a crucial component of protecting habitat for these species that occur on BLM-managed lands.

The BLM believes that instream flow protection for native fishes residing in Milk Creek can be achieved while allowing water to be developed and used for current and future needs, including industrial and agricultural uses. BLM is willing to meet with water users and stakeholders within the watershed to discuss any concerns they may have about the impact of the proposed appropriation on future water uses and development. BLM is also willing to provide all supporting data to interested parties for their review. An attachment to this letter provides specific information that supports BLM's instream flow recommendation, including biological characteristics of Milk Creek, habitat modeling, water availability for instream flow protection, and recommended flow protection rates.

BLM requests the Colorado Water Conservation Board (CWCB) proceed with its appropriation process at the regularly scheduled board meeting in March 2025, given that outreach to stakeholders in the watershed have not revealed any significant reasons for a delay. If you have any questions regarding this formal recommendation, please contact Roy Smith at 303-239-3940.

Sincerely,

JOEL HUMPHRIES Digitally signed by JOEL HUMPHRIES Date: 2025.02.27 09:45:02 -07'00' for

Alan Bittner
Deputy State Director
Resources

Enclosure:
BLM Milk Creek Instream Flow Recommendation

cc:
Kymm Gresset, Little Snake Field Office
Eric Scherff, Little Snake Field Office
Bob Swithers, Northwest District

BLM Instream Flow Recommendation for Milk Creek

February 2025

BLM Instream Flow Recommendation for Milk Creek
Section 1 - Biological Summary

Physical Habitat

This portion of Milk Creek is a low to moderate gradient stream in a canyon approximately 0.5 miles in width. In some locations, there is sufficient width in the canyon bottom for the stream to meander over time. In other locations, stream movement is confined by bedrock. The creek stream has a stable channel but has a highly variable substrate size, ranging from gravels to 2-foot diameter boulders. The stream has a good mix of riffle, run, and pool habitat to support native fish populations. Water quality, water temperatures, and food sources are also suitable for native species.

Native Fishery

Fishery surveys indicate that the lowest 4.1 miles of Milk Creek provides habitat for native species, including Flannelmouth Sucker *(Catostomus latipinnis)*, Bluehead Suckers (*Catostomus discobolus*), Roundtail Chub (*Gila robusta*), and Speckled Dace (*Rhinichthys osculus*). Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub (the "Three Species") 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 Three Species meet the first two of the criteria listed above, qualifying them as BLM "sensitive species."[1]

All three species are listed in the Colorado State Wildlife Action Plan (2012) as Tier 1 Species of Greatest Conservation Need, or "species which are truly of highest conservation priority in the state." The Three Species are exhibiting a downward trend and collectively occupy less than half of their historic native range in the Colorado River Basin overall.[2]

Milk Creek provides important spawning habitat for adult populations of the Three Species that reside in the Yampa River. Very few significant perennial tributaries enter the Yampa River at the low elevations that are required for native fish spawning habitat, so Milk Creek provides important habitat for restoring native fish populations in the Yampa River watershed. Tributary habitats provide unique refugia for juvenile native fish where threats of predation and hybridization with non-native species may be substantially lower than those in the mainstem Yampa River.

Recognizing the importance of the Milk Creek habitat, BLM and CPW have taken the following actions:

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[1] www.blm.gov/programs/wildlife/threatened-and-endangered/blm-special-status-species
[2] Bezzerides, N. and K. Bestgen. 2002 Status review of Roundtail Chub, Flannelmouth Sucker, and Bluehead Sucker in the Colorado River Basin. Larval Fish Laboratory, Colorado State University, Fort Collins.

- CPW has stocked 20,632 Bluehead Suckers and 3,549 Flannelmouth Suckers in the creek since 2015. The objective of the stocking effort is to augment populations in the Yampa River that have been reduced by predation by non-native fishes. The stocked fish were adults fitted with Passive Integrated Transponder (PIT) tags prior to release that are large enough to avoid predation by small mouth bass.

- Since Bluehead Sucker stocking was initiated, BLM and CPW have utilized PIT tag arrays to monitor their use of and affinity to Milk Creek.

- BLM and CPW have removed nonnative competitive species during all fish survey efforts.

Nonnative Fishery

Non-native fish species that utilize Milk Creek include Black Bullhead (*Ameiurus melas*), Brook Stickleback (*Culaea inconstans*), Brown Trout (*Salmo trutta*), Common Carp (*Cyprinus carpio*), Creek Chub (*Semotilus atromaculatus*), Fathead Minnow (*Pimephales promelas*), Green Sunfish (*Lepomis cyanellus*), Iowa Darter (*Etheostoma exile*), Northern Plains Killifish (*Fundulus kansae*), Red Shiner (*Cyprinella lutrensis*), Sand Shiner (*Miniellus stramineus*), Smallmouth Bass (*Micropterus dolomieu*), White Sucker (*Catostomus commersonii*), White x Bluehead Sucker Hybrid, and White x Flannelmouth Sucker Hybrid.

Macroinvertebrates

Aquatic macroinvertebrates are an important component of aquatic food webs and serve as an important food source for fish. In October 2023, CPW staff collected macroinvertebrate samples using CPW's River Watch kick-net sampling procedure. Two samples were collected at different locations within the ISF reach and analyzed using a 500-count sub-sample. Taxa identified from the two samples were odonata, ephemeroptera, plecoptera, tricoptera, decapoda, coleopteran, diptera, and amphipoda. Of primary interest are the EPT taxa – ephemeroptera (mayflies), plecoptera (stoneflies), and tricoptera (caddisflies) – all of which were observed at both sampling locations. The presence and abundance of EPT taxa reflect the health of aquatic systems.

Riparian Community

The creek supports a riparian community comprised primarily of willows, sedges, cottonwoods, and rushes. The riparian community has been impacted by historical grazing practices but is now on an upward trend in lower portions of the reach and is static farther upstream. This reach also hosts mature cottonwood trees, and substantial cottonwood regeneration has been observed.

BLM Instream Flow Recommendation for Milk Creek
Section 2 - Flow Quantification Methodology and Results

System for Environmental Flow Analysis (SEFA)

In 2023, CPW, BLM, and CWCB embarked on a collaborative effort to collect cross section, flow, and substrate data to identify flow rates needed to support the adult and spawning life stages of the Three Species. The three agencies employed the System for Environmental Flow Analysis (SEFA), which is used to simulate the relationship between streamflow and physical habitat available to various life stages of fish species. The SEFA model is part of Instream Flow Incremental Methodology (IFIM), and it is used across the U.S. to identify specific flow rates needed to maintain fish habitat. The three agencies elected to utilize SEFA because it supports the development of instream flow recommendations that are specific to the habitat needs of Flannelmouth Suckers and Bluehead Suckers. Even though SEFA requires extensive data collection over time, CPW and BLM believed the investment was warranted because of the importance of habitat in lower Milk Creek for sensitive fish species.

CPW and the BLM originally planned to use the PHABSIM (Physical Habitat Simulation) software for the instream flow evaluation in Milk Creek. 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. PHABSIM has been widely used in North America to quantify instream flow requirements, and it has been utilized previously by CWCB to quantify instream flow appropriations.

PHABSIM is now legacy software and is no longer supported for current Windows operating systems. SEFA includes all the hydraulic and habitat simulation functions of PHABSIM and includes additional capabilities to model sediment transport, bioenergetics, water temperature, dissolved oxygen, fish passage and hydrology and habitat time series. SEFA also has the capability to predict fish passage through a study site. The passage criteria can be specified in the analysis and the model calculates the amount of width available for fish passage through the site. SEFA also calculates maximum depth for each cross section and at various flow rates. The fish passage analysis and maximum depth prediction provide the data needed for the determination of a minimum flow that provides longitudinal connectivity in the study site and the reach.

CWCB contracted with Freshwater Consulting, LLC to provide guidance in selecting field sites, data collection techniques, and developing habitat suitability indices. Freshwater Consulting also ran the SEFA model and provided a report summarizing model results. [3]

Study Area

The study area extended from the Yampa River confluence to approximately four miles upstream. The Milk Creek study sites are located approximately 0.5 miles (Site 1) and 0.9 miles (Site 2) upstream from the confluence of Milk Creek and the Yampa River. The entire four-mile study area was evaluated prior to the site selection. The two study locations were selected as

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[3] All study data that supports this section of the CPW and BLM instream flow recommendation can be found in Miller, William J., PhD, *Final Milk Creek Instream Flow Study Report*, September 30, 2024.

representative of the habitat within the lower four miles of Milk Creek. Both sites include all habitat types present within the study area, which include riffle, run and pool habitat with stream substrates that range in size from fine silt to large cobble. Both sites have multiple sequences of these habitat types and are representative of the overall reach habitat characteristics.

Field Data Collection and Model Input

Stream cross sections were established in each habitat type at each study site with a metal headpin on the right bank above the high-water mark. The cross sections were placed perpendicular to stream flow with wooden stakes as working pins on both banks. Eight cross sections were monumented at each study site. Standard survey techniques were used to establish elevations of all headpins and bed profile elevations relative to a benchmark. Water depth and velocity were measured using a topset wading rod and digital flow meter.

During 2023 and spring 2024, additional water surface data was collected at both sites, with flow rates of 6.26 cfs, 44.5 cfs, and 127.6 cfs at Site 1 and at 6.06 cfs, 52.2 cfs, and 127.6 cfs at Site 2. These additional measurements are referred to as calibration measurements in SEFA, and they allow the model to more accurately predict habitat availability at various flow rates.

Data from the site visits were entered into computer spreadsheets and imported into SEFA software for analysis. SEFA software processing included data entry, hydraulic model calibration, hydraulic model simulations, habitat suitability criteria entry, and hydraulic-habitat model simulations.

Habitat Suitability Criteria and Area Weighted Suitability

Habitat suitability criteria describe a habitat's ability to support a particular life stage of a fish species. It is expressed in a numerical format that specifies the stream depths, velocities, and substrate types that a species will use. These criteria are applied to the stream hydraulic characteristics documented at various flow rates to calculate the amount of usable habitat for each species and life stage.

For this study, the habitat suitability criteria for adult Flannelmouth Sucker were updated in early 2024. The update drew from a combination of data from radio telemetry studies on the Colorado River near Grand Junction, existing data from a range of rivers, and literature review of habitat and population studies. Limited data is available specific to Bluehead Sucker habitat preferences, so the habitat suitability criteria for Flannelmouth Sucker were also used for Bluehead Sucker in this study. Bluehead Sucker feed by scaping on hard substrates and are known to feed in faster riffle habitat with cobble and boulders whereas Flannelmouth Sucker feed on softer substrates in somewhat slower velocities. Accordingly, the habitat response shown for Flannelmouth Sucker approximate habitat response to flow for Bluehead Sucker but will not fully depict all areas suitable for Bluehead Sucker. The suitability indices used in the hydraulic-habitat modeling are a combination of the data from Flannelmouth Sucker and Bluehead Sucker studies on the Colorado River and literature from the U.S. Fish and Wildlife Service.

Flannelmouth Sucker and Bluehead Sucker spawn in riffle habitat over gravel and cobble substrate. Spawning habitat use is generally restricted to shallower depths and higher velocity than the broader habitat types used by adults. The spawning habitat suitability criteria for both species were based on a combination of literature review and existing habitat suitability criteria from the U.S. Fish and Wildlife Service. Suitable spawning substrate material was restricted to gravel and cobble substrate types in the model to accurately reflect the use of these sites during spawning.

In SEFA, the amount of habitat calculated to be available at various flow rates is referred to as "Area Weighted Suitability" (AWS). The results of the hydraulic-habitat function are expressed as area (ft^2) per linear distance (ft). The AWS is the Combined Suitability Index (CSI) for depth, velocity and substrate for each measurement point weighted by the area the point represents.

Fish Passage

Longitudinal connectivity is important in riverine systems to allow migration and localized movement required by fish and other aquatic biota. Flannelmouth Sucker and Bluehead Sucker migrate from larger rivers into smaller tributary streams such as Milk Creek for spawning, and habitat connectivity is critical for that life stage. Analysis of fish passage is one means to assess connectivity and evaluate the flows needed to allow fish migration.

SEFA has the capability to predict fish passage through a study site. The passage criteria can be specified in the analysis and the model calculates the amount of width available for fish passage through the site. SEFA also calculates maximum depth for each cross section and simulated flow. The fish passage analysis and maximum depth prediction provide the data needed for the determination of a minimum flow that provides longitudinal connectivity within the study site and through the reach.

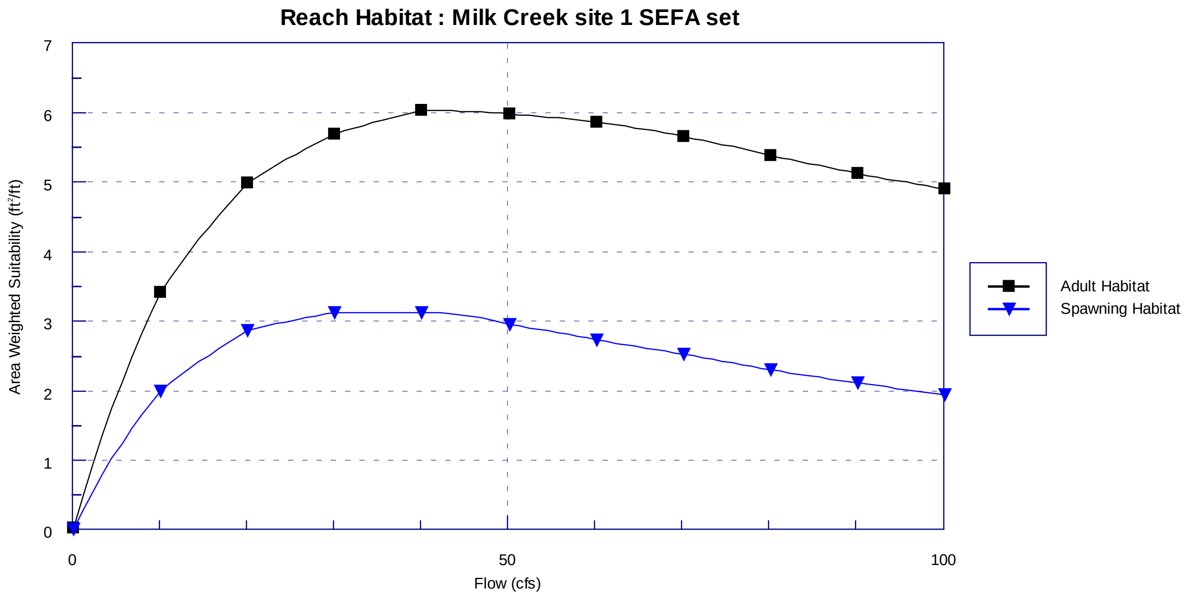
SEFA Modeling Results

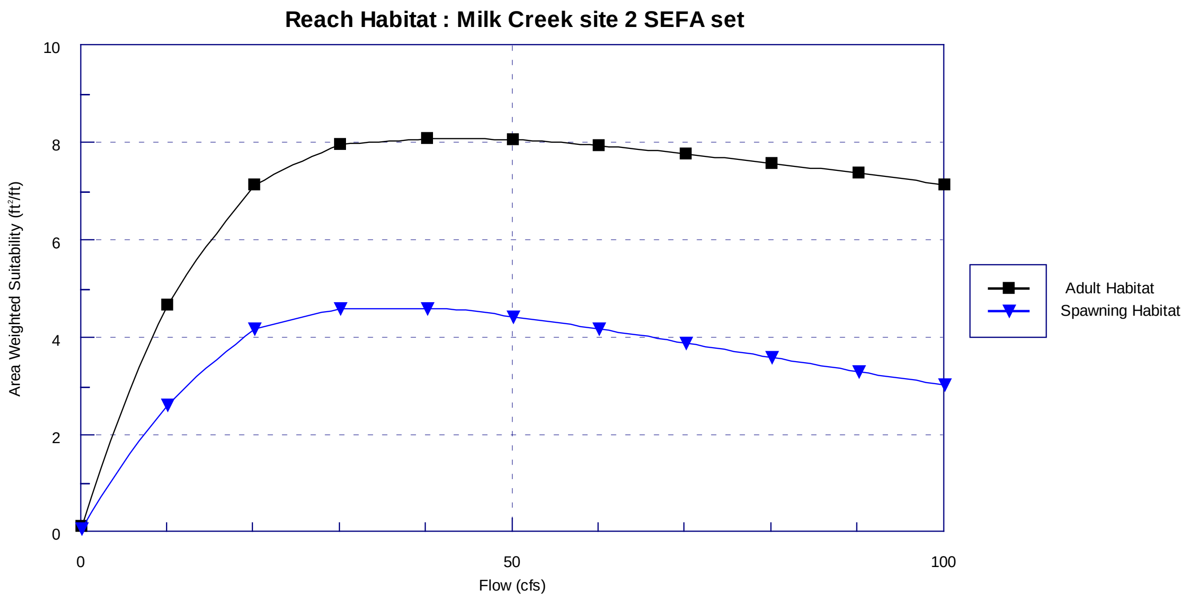
Modeling to identify hydraulic characteristics for each site was completed for flows ranging from 5.0 to 300.0 cfs. Because data were collected at a range of flow rates from base flows to snowmelt runoff flows, the R-square for the rating curves at each site was close to 1.0. Accordingly, no model calibration was required to derive accurate estimates of hydraulic characteristics. Hydraulic-habitat simulations were completed for flows from 5 cfs to 100 cfs at each site. A fish passage analysis was completed after the hydraulic-habitat simulations to evaluate longitudinal connectivity at base flows.

The modeling revealed that maximum AWS for adult sucker habitat occurs at a flow of 40 cfs at both sites. AWS rapidly decreases for adult habitat as flow drop below 40 cfs. A flow of 10 cfs results in approximately 60% of the maximum habitat index. The habitat index has a less rapid decline when flows exceed 40 cfs. A flow of 100 cfs still has approximately 80% of the maximum habitat index.

The maximum AWS for spawning habitat occurs from 30 cfs to 40 cfs for both sites. There is very little difference between the spawning habitat index value at 30 cfs and 40 cfs. The shape of the AWS versus discharge function for spawning habitat is similar to the adult habitat discharge function with a steep decline in habitat as flows drop below 30 cfs. A flow of 10 cfs produces approximately 65% of the maximum potential habitat at Site 1 and approximately 58% of the maximum habitat potential at Site 2. The spawning habitat index at 100 cfs is slightly higher than 60% of the maximum habitat index at both sites.

The figures below show AWS as a function of discharge for adult and spawning Flannelmouth Suckers and Bluehead Suckers.





In addition to calculating AWS at various flow rates, a fish passage criterion of 0.6 foot (7 inches) of depth was chosen based on professional judgement to evaluate fish passage for the native suckers. This depth is approximately double the body depth of adult Flannelmouth Suckers (the larger of the two species), which should allow passage. The SEFA fish passage/connectivity analysis for Milk Creek showed that at a flow of 8.0 cfs, there is a continuous pathway for fish passage through all cross sections that is at least 2 feet in width and at least 0.6 feet in depth at Milk Creek Site 1 and Milk Creek Site 2.

BLM Instream Flow Recommendation for Milk Creek
Part 3 – Recommended Flow Rates and Rationale

Development of Flow Recommendations

The recommended flow values were determined using the best professional judgment of CPW and BLM biologists and hydrologists, and they are designed to protect a reasonable amount of habitat for native fishes. The initial biological flow recommendations produced by the SEFA modeling were adjusted to reflect water availability. The recommendations consider the needs of various species and their life stages, and habitat usage at various time of the year. In addition, the recommended flow rates consider the vital function that Milk Creek plays in providing spawning habitat for native fishes in the Yampa River. The recommended flow rates are as follows:

<u>40.0 cfs – April 1 through June 30</u>

A flow rate of 40 cfs maximizes preferred habitat across both SEFA sites. It appears that 40 cfs is available at least 50% of the time between April 1 and June 30, so no water availability adjustment was required during this time period. Snowmelt runoff generally occurs from mid-April to mid-June, and it has multiple benefits for native species. First, snowmelt runoff flows clear riffles of sediment and often re-set bed sediments to provide optimal aeration for deposited eggs. Second, snowmelt runoff flows are critical for maintaining habitat diversity within the stream channel, which supports all life stages of native fish. Especially important for emerging fry are side-channel and backwater sites that become refugia for young fish following snowmelt runoff flows. Third, peak flows are critical for redistributing sediments, creating new instream and near-stream habitat. Spawning for Bluehead Suckers and Flannelmouth Suckers may occur during pre-peak or post-peak periods. Fry emergence and dispersal shortly thereafter (7-10 days) is aided by continuing high flows and subsequent drift to side-channel, backwater, channel margins, and other low velocity sites. A flow rate of 40 cfs will provide optimal habitat availability beginning on the rising limb of the hydrograph and through the receding limb. This will support adequate depth and velocity for adult and spawning native fish. This flow rate will also provide a ramp during and after peak flows that helps with the lifecycle requirements of native fish (specifically incubation of eggs and dispersal of emerged larvae in channel margins).

<u>8.0 cfs - July 1 through July 31</u>

After June, flows decrease rapidly because of declining natural water availability and strong irrigation demand upstream. The descending limb of the hydrograph occurs at the warmest time of the year when the species are most active, and when the species are attempting to put on weight to survive limited food availability during winter. This recommended flow rate is based on maintaining longitudinal connectivity of habitat during this critical time of the year, when fingerlings, fry, emerged larvae, and developing eggs are moving from nursery areas in Milk Creek to the habitat in the Yampa River.

The SEFA model showed that a flow of 8.0 cfs will provide a continuous pathway for fish passage through all cross sections that are at least 2 feet in width and at least 0.6 feet in depth at

Milk Creek Site 1 and Milk Creek Site 2. This recommended flow rate is based on maintaining longitudinal connectivity of habitat during the transitional period between snowmelt runoff conditions and baseflow conditions.

4.5 cfs - August 1 through September 30
5.2 cfs - October 1 through December 31
7.8 cfs – January 1 through February 29

The three recommended flow rates above are based on limited water availability during the base flow period. Fish surveys have revealed that some native species use Milk Creek during this period, even though the mobility of fish between habitat types is limited. CPW and BLM believe that protecting these flow rates are critical for maintaining habitat for resident native fishes, and that limited flows during this period also reduce habitat occupancy by predatory non-native fishes. Adequate baseflow conditions are critical for survival of native fish for several reasons. Native suckers, particularly Bluehead Suckers, are primarily foraging fish that feed on algae and detritus within the stream channel, and incidental to consumption of vegetation by these fish is the consumption of a number of high-protein macroinvertebrates that also feed on or inhabit riverine plants. This primary and secondary production within the channel is highly dependent on riffles that have both good aeration and available sunlight. Growth during summer baseflow months is critical to provide fish the resilience needed to survive the winter, when forage is scarce. Baseflow during winter months is necessary to provide enough habitat variety to overwinter both young-of-year, and juvenile, fish, and to provide enough mobility so that fish can escape predation or find more advantageous habitats as seasonal conditions evolve.

18.0 cfs – March 1 through March 31

As low elevation snowmelt runoff begins, it is important to protect flows that allow the populations to move between habitat types. Protection of higher flows associated with the beginning of snowmelt runoff is warranted during this period because it is the beginning of the portion of the year when native fishes complete critical parts of their life cycles, including the commencement of spawning activities in early spring. Both Flannelmouth Sucker and Bluehead Sucker have been documented to start spawning in streams in western Colorado during March.

Low elevation streams in western Colorado often surge in response to melt of low elevation snowpack, spring storms, and early ripening of the snowpack in higher terrain. Water also begins warming in response to longer days and warmer air temperatures. Along with an increasing photoperiod, these hydrologic cues signal native fish to navigate toward likely spawning sites. Flannelmouth Suckers and Bluehead Suckers have been known to travel long distances toward habitual spawning areas. Increased flows during this period also mobilize fine sediments that may have settled during localized late-summer or fall monsoon storms, improving conditions in cobbles for spawning.

Summary

This recommendation recognizes that the Three Species evolved within the Colorado Plateau, a region that is hydrologically diverse and variable. Optimal conditions for spawning, growth, and survival were typically unpredictable. Adaptations of these fishes to accommodate this variability include their relatively large body sizes and longevity, as well as their egg-dispersal mechanisms, which favored high volume and low investment in terms of energy required to nurture and care for emerging fry. In essence, these adaptions reflect the hydrologic landscape from which they evolved. Any instream flow water right should maintain, on a minimum basis, the seasonal variations in conditions required for these native fish to persist in Milk Creek.

COLORADO
Parks and Wildlife
Department of Natural Resources

Water Resources Section – Aquatics
Branch
6060 Broadway
Denver, CO 80216

March 7, 2025

Rob Viehl, Section Chief
Colorado Water Conservation Board (CWCB)
Stream and Lake Protection Section
1313 Sherman Street, 7th Floor
Denver, CO 80203

Re: Colorado Parks and Wildlife and Bureau of Land Management Instream Flow Recommendations for Milk Creek in Moffat County

Dear Mr. Viehl:

The purpose of this letter is to formally transmit Colorado Parks and Wildlife's (CPW) instream flow (ISF) recommendations for Milk Creek in Water Division 6. This ISF recommendation is a joint recommendation from CPW and the Bureau of Land Management (BLM). BLM initially began work on this ISF recommendation in 2016. Milk Creek is an important tributary of the Yampa River that supports native Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub, an assemblage of native fishes often referred to as the "Three Species." The Three Species are listed in the Colorado State Wildlife Action Plan (SWAP) as a Tier 1 Species of Greatest Conservation Need or "species which are truly of highest conservation priority in the state." The Three Species are exhibiting a downward trend and collectively occupy less than half of their native range in the Colorado River Basin. Milk Creek is known to provide spawning habitat and unique refugia for the Three Species which makes it an important tributary supporting their overall persistence in the Yampa River basin. In light of these factors, CPW became involved in the ISF recommendation in 2023 to support the BLM and co-recommend ISF water right protection for a segment of lower Milk Creek near the confluence with the Yampa River.

CPW and BLM are recommending an ISF reach on Milk Creek from the confluence with Wilson Creek to the confluence with the Yampa River, a distance of approximately 4.1 miles. This segment is in Moffat County. Land ownership over the proposed ISF reach is a combination of BLM-managed lands and lands under private ownership. This segment of Milk Creek is important to CPW for a number of reasons. Most importantly, it is known to provide spawning and rearing habitat for the Three Species. CPW is a signatory, along with the BLM, other federal agencies, and multiple tribes, to the Range-Wide Conservation Agreement and Strategy for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker [1]. The goal of the Conservation Strategy is to ensure the persistence of populations of the Three Species

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[1] Utah Division of Wildlife Resources (UDWR). 2019. Range-wide conservation agreement and strategy for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker. Publication Number 06-18. Prepared for Colorado River Fish and Wildlife Council. Utah Department of Natural Resources, Division of Wildlife Resources, Salt Lake City, Utah.

throughout their respective ranges. CPW seeks to reduce the imperiled status of these species across their historic range in Colorado in order to protect the species and to reduce the risk of a federal listing as threatened or endangered under the Endangered Species Act (ESA). Factors contributing to their decline include hydrologic alteration, lack of connectivity, and predation by and hybridization with non-native species.

CPW has dedicated significant resources to bolstering these populations through non-native fish control, reservoir screening projects, research on movement patterns and spawning behavior in tributaries like Milk Creek, and supplemental stocking to augment populations. Protecting flows in a unique tributary environment like Milk Creek is a complementary action to these efforts. From 2015 to 2024, CPW has proactively stocked Bluehead Sucker and Flannelmouth Sucker in Milk Creek to bolster populations in both Milk Creek and the Yampa River. This effort was the first of its kind to stock small numbers of Bluehead and Flannelmouth Suckers with the goal of augmenting the Milk Creek population and hopefully reestablishing populations of these species throughout the Yampa River basin via dispersal from Milk Creek. Milk Creek provides unique habitat characteristics that support Bluehead and Flannelmouth Sucker, namely spring high-flow events that are beneficial for spawning, appropriate water temperature, suitable geomorphology, and high turbidity. Spring-time and sporadic high-flow events also discourage establishment of non-native species in Milk Creek. By boosting populations in important tributary environments like Milk Creek, additional populations may also become established in the Yampa River mainstem where non-natives are suppressed by non-native fish control efforts. Working with the Colorado Water Conservation Board (CWCB) to secure an ISF water right is an appropriate tool for protecting streamflows that are critically important for the persistence of the Three Species.

Natural Environment

Milk Creek is a tributary to the Yampa River downstream from the City of Craig, Colorado. It is the largest tributary to the Yampa River between the confluence of the Williams Fork and Little Snake Rivers and provides important seasonal spawning habitat for the native Three Species. The lower segment of Milk Creek has a low to moderate gradient, approximately 0.5 percent[2]. The creek has a stable channel with variable substrate ranging from silt to large boulders. The stream has a good mix of riffle, run, and pool habitat. The macroinvertebrate community is healthy and diverse. Water quality, water temperatures, and food sources are suitable for native species. Fishery surveys indicate that lower Milk Creek provides habitat for native species, including Flannelmouth Sucker, Bluehead Sucker, Roundtail Chub, Mountain Sucker, and Speckled Dace. Non-native fish species have also been sampled by CPW in the creek and include Smallmouth Bass, Creek Chub, Sand Shiner, Red Shiner, White Sucker, Brook Stickleback, Fathead Minnow, Black Bullhead, Johnny Darter, Plains Killifish, Green Sunfish, and Bluegill. The creek supports a riparian community comprised primarily of willows, sedges, cottonwoods, and rushes. The riparian community has been impacted by

[2] Freshwater Consulting LLC. September 30, 2024. Milk Creek Instream Flow Study Report.

historical grazing practices but is improving in lower portions of the reach. The ISF reach includes mature cottonwood trees and notable cottonwood regeneration has been observed.

Native Three Species Usage of Milk Creek

As mentioned above, Milk Creek provides year-round and seasonal habitat for the Three Species. Milk Creek experiences a snowmelt-driven hydrograph, with peak flows occurring as spring temperatures begin to rise. The area also can experience monsoonal rains in the late summer, which can dramatically raise the water level in the creek. There is heavy use by adult Three Species during the spring runoff period and receding limb, specifically Bluehead Sucker and Flannelmouth Sucker. The Three Species have been known to travel long distances toward habitual spawning areas. During the rising limb of the hydrograph when the water temperature reaches approximately 13°C, Flannelmouth Sucker migrate into tributaries to spawn. Bluehead Suckers follow shortly after, once water temperature reaches 16°C. In Milk Creek this window typically occurs between April to mid-May annually but can vary significantly from year-to-year. Roundtail Chub can be found in Milk Creek and its tributary Stinking Gulch but their densities are low near the Yampa River confluence. This is likely driven by low densities of Roundtail Chub in the Yampa River. Most of the Roundtail Chub in lower Milk Creek are juveniles. Roundtail Chub of all life stages are present higher in the drainage above Axial Basin.

Due to deep water and swift flows, typical fishery survey methods are not efficient in Milk Creek during the spring runoff period when adult native fish occupy the creek. CPW uses submersible Passive Integrated Transponder (PIT) tag antennas deployed in Milk Creek to evaluate Three Species usage in the creek. PIT tags are used to track both stocked Bluehead Sucker and Flannelmouth Sucker and wild captured Three Species that are routinely encountered in both Milk Creek and the Yampa River. When individuals are recaptured or detected on submersible antennas, CPW can evaluate annual movement patterns throughout the Upper Colorado River Basin. Growth rates can also be tracked on recaptured individuals. Since 2015, approximately 20,949 Bluehead Suckers and 3,549 Flannelmouth Suckers were stocked by CPW in Milk Creek as sub-adults to supplement populations in the Yampa River. Antenna data shows that native suckers from Milk Creek mature in the creek and move into the Yampa River as flows in Milk Creek recede to baseflows. Many adults, both wild and hatchery-reared, return to Milk Creek to spawn in the spring. Milk Creek offers unique habitat refugia where there is less predation from non-native fish species in the Yampa River and less opportunity for hybridization with non-native sucker species.

Because of inclement weather conditions in northwestern Colorado during early spring and unmaintained dirt road access to Milk Creek, deploying PIT tag antennas during this critical window can be challenging. Some years CPW staff are only able to capture the tail-end of the spawning migration with antenna data, as demonstrated by detection data from 2023. However, 2022 is a good example of a spawning migration captured with antenna detections with a majority of the wild native fish species using Milk Creek between April and June (see Milk Creek Fish Community and Movement Summary Figures 6 and 7).

Macroinvertebrate Community

Aquatic macroinvertebrates are an important food source for fish and can serve as a biocriteria to evaluate the overall health of the aquatic ecosystem. In October 2023, CPW staff collected macroinvertebrate samples using CPW's River Watch kick-net sampling procedure. Two samples were collected at different locations within the ISF reach and analyzed using a 500-count sub-sample. Taxa identified from the two samples were odonata, ephemeroptera, plecoptera, tricoptera, decapoda, coleopteran, diptera, and amphipoda. Additionally, hemiptera taxa were also visually identified at both sites but were not captured in the kick-net surveys. CPW staff ran macroinvertebrate results in Colorado Department of Public Health (CDPHE) Ecological Data Application System (EDAS) program. Based on these results summarized below, both sites are attaining and meeting the state standards for macroinvertebrate health and biodiversity.

The multimetric index (MMI) scores were above the state Policy 10-1[3] thresholds. In fact, the upper site is a "High Scoring Water" with an MMI score greater than 56. Two auxiliary metrics in addition to MMI scores are considered by the state when assessing macroinvertebrate communities - the Hilsenhoff Biotic Index (HBI) and Shannon Diversion Index (SDI). HBI is an indicator of pollution tolerant insects occupying the creek where higher scores indicate a pollutant-tolerant community. The HBI scores for Milk Creek are below the state threshold of 5.8 which indicates relatively few pollution tolerant species. The SDI metric shows how biodiverse the community is with higher scores indicating more biodiversity. Both sites have fairly high SDI scores that are well above the state threshold of 2.1 (note, a maximum SDI score is 5).

Station	Waterbody	Location	Date	Biotype	MMI	HBI	SDI
WQCC Policy 10-1 Thresholds				**1 - Transition**	**> 45**	**< 5.8**	**> 2.1**
RW-3870	Milk Cr	Upper Milk Creek	16-Oct-23	1	68.2	4.9	3.1
RW-3871	Milk Cr	Lower Milk Creek	16-Oct-23	1	54.1	3.9	3.8

Additional metrics evaluated by CPW staff are focused on sensitive macroinvertebrate species – ephemeroptera (mayfly), Plecoptera *(*stonefly), and Trichoptera (caddisfly). These orders are also known as "EPT" taxa. The metric "% EPT non Baetidae" evaluates how many insects belong to the EPT orders excluding Baetidae. Baetidae are a type of mayfly that is tolerant of pollution so they are intentionally excluded from this metric. At both sites, almost half of the

[3] CDPHE. August 10, 2020. Policy Statement 10-1. Aquatic Life Use Attainment Methodology to Determine Use Attainment for Rivers and Streams

insects belong to pollution intolerant EPT orders which is a sign of an overall healthy aquatic ecosystem. Similarly, the "% Intolerant taxa" category involves pollution intolerant taxa not limited to EPT taxa. At both sites, there is a strong presence of pollution intolerant taxa with samples containing 36% and 21.7% pollution intolerant taxa. At both sites, there was a high number of unique species with Total Taxa of 25 and 23. This demonstrates a community that is species-rich with relatively high biodiversity.

Station	Waterbody	Location	EPT % non Baetidae	% Intolerant Taxa	Total Taxa
RW-3870	Milk Cr	Upper Milk Creek	45.9	36	25
RW-3871	Milk Cr	Lower Milk Creek	48.4	21.7	23

ISF Quantification

Methodology – Instream Flow Incremental Methodology (IFIM) using System for Environmental Flow Analysis (SEFA)

CPW and BLM utilized professional judgement and past experiences to determine the appropriate methodology for use in the Milk Creek ISF recommendation. The BLM and CPW decided to use a methodology that is species-specific and can be tailored to assessing flow and habitat relationships specific to Flannelmouth Sucker and Bluehead Sucker. BLM and CPW decided to use the Instream Flow Incremental Methodology (IFIM), a widely accepted method for quantifying suitable hydraulic habitat as a function of discharge for specific species and life stages of fish. In 2023, CWCB hired Freshwater Consulting LLC to provide field support and technical training necessary to complete a hydraulic habitat model on Milk Creek using the System for Environmental Flow Analysis (SEFA). The SEFA software is a modern version of the Physical Habitat Simulation software (PHABSIM), a program which was historically used for all of Colorado's instream flow evaluations using the IFIM framework. As legacy software, PHABSIM was not updated for compatibility to Windows Operating System 11. The SEFA software is the modern equivalent with additional features, one of which is the predicting fish passage across transects. Freshwater Consulting trained BLM, CPW, and CWCB staff in field methods and use of the SEFA software, developed the models, and completed a summary report (Freshwater Consulting, 2024).

In fall of 2023, Freshwater Consulting, BLM, CPW, and CWCB staff performed site selection and field data collection to build a hydraulic habitat model for the Milk Creek ISF reach in SEFA. After assessing the four-mile ISF reach, a study area was selected that is representative of the ISF reach. Two study sites were surveyed on BLM lands – Site 1 was approximately 0.5 miles above the confluence with the Yampa River and Site 2 was approximately 0.9 miles above the confluence. The two study sites include a variety of riffle, run and pool habitat types with bed substrate that ranges in size from fine silt to large cobble. Surveys were conducted in October 2023 to establish bed topography. An initial hydraulic habitat-discharge relationship was analyzed under baseflow conditions (approximately 6 cfs). In spring 2024, two additional sets of measurements were made to calibrate the model over a range of flows, these include measurements at a mid-range flow (approximately 45-50 cfs in April) and a high flow (approximately 127 cfs in June).

Habitat Suitability Criteria (HSC)

Habitat suitability criteria (HSC) represent a fish species' preference for habitat variables such as depth, velocity, substrate, or cover. For this ISF evaluation, HSC for adult Flannelmouth Sucker and Bluehead Sucker were updated in early 2024 by Miller Ecological Consultants[4]. A combination of data was used including radio telemetry studies on the Colorado River near Grand Junction, existing occupancy data from a range of rivers, and a literature review of habitat and population studies. There is relatively limited habitat suitability data specific to Bluehead Sucker, so HSC for Flannelmouth Sucker were used as a surrogate. Bluehead Sucker have different feeding preferences than Flannelmouth Sucker and are known to feed by scraping algae and periphyton from cobble-sized substrates in faster riffle habitats. Flannelmouth Sucker tend to feed on aquatic invertebrates and detritus found in finer substrates in habitats with relatively low velocities. Given these differences, the habitat response shown for Flannelmouth Sucker approximates habitat response to flow for Bluehead Sucker but will not fully depict all areas suitable for Bluehead Sucker. The suitability indices used in the hydraulic-habitat modeling are a combination of the data from Flannelmouth Sucker and Bluehead Sucker studies on the Colorado River and literature from the U.S. Fish and Wildlife Service, as summarized by Miller Ecological Consultants (Miller, 2024).

Flannelmouth Sucker and Bluehead Sucker spawn in riffle habitat over gravel and cobble substrate. Spawning habitat use is generally restricted to shallower depths and higher velocity habitats than the broader habitat used by adults. The spawning HSC for both species were based on a combination of literature review and existing habitat suitability criteria from the U.S. Fish and Wildlife Service (Miller, 2024). Suitable spawning substrate material was restricted to gravel and cobble substrate types in the model to accurately reflect the use of these sites during spawning.

Area Weighted Suitability (AWS) and Fish Passage Criteria

In SEFA, the amount of suitable habitat computed at various flow rates is referred to as Area Weighted Suitability (AWS). Results for combined AWS for depth, velocity, and substrate are shown below for the two study sites:

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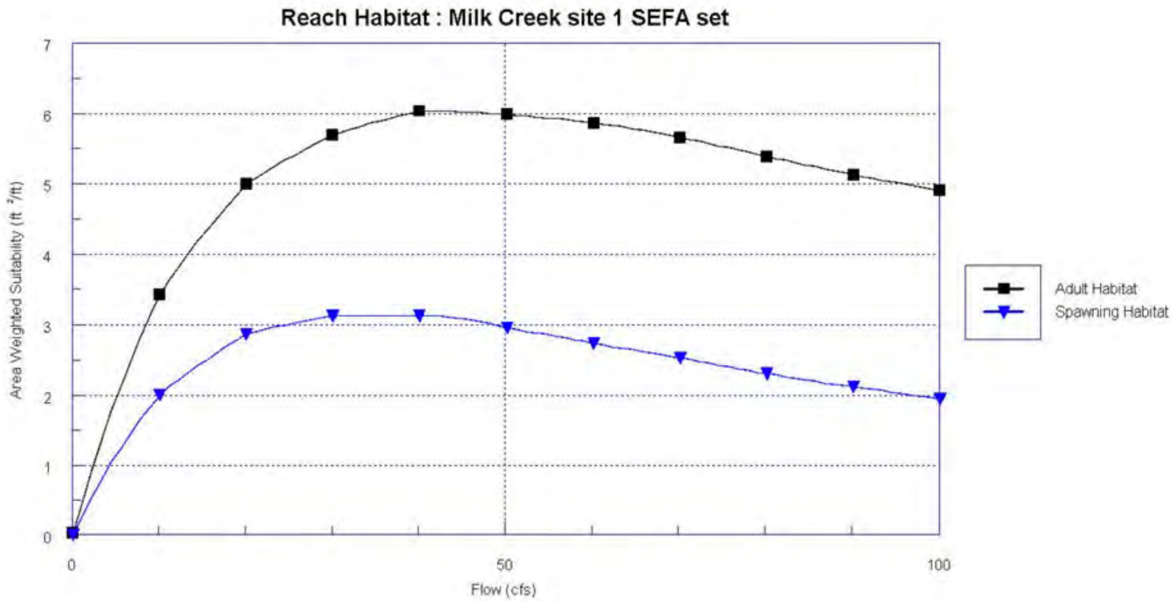
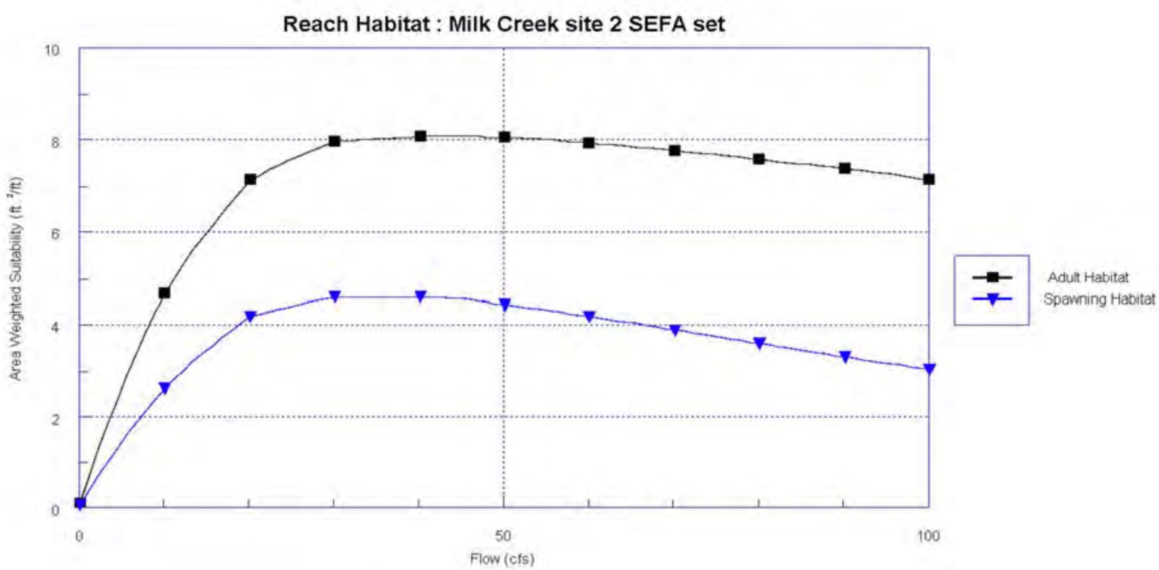
[4] Miller Ecological Consultants. January 26, 2024. Proposed Habitat Suitability Criteria for Flannelmouth Sucker and Bluehead Sucker for use in Milk Creek Instream Flow Study





The hydraulic habitat modeling results for both sites were comparable with maximum AWS for occurring at a flow of 40 cfs for adult sucker species. For spawning habitat, the highest AWS occurs from 30 cfs to 40 cfs for both sites. For both general adult habitat and spawning habitat, AWS decreases rapidly below 40 cfs, indicating that additional increments of discharge provide significant habitat response benefits as flows approach 40 cfs. At flows greater than 40 cfs, additional increments of discharge provide smaller habitat benefits.

In addition to calculating AWS at various flow rates, a fish passage assessment was conducted using a depth criteria of 0.6 feet (7 inches). This was chosen based on professional judgment as this depth is approximately double the body depth of an adult Flannelmouth Sucker. This is protective of Bluehead Sucker because Flannelmouth Sucker is the larger of the two species. The SEFA fish passage connectivity evaluation showed that at a flow of 8.0 cfs, all cross-sections measured show a continuous pathway for fish passage that is at least 2 feet in width and at least 0.6 feet in depth at both study sites.

Instream Flow Recommendations

Using the approach and results summarized above, CPW and BLM developed the following instream flow recommendations. Based on the CWCB's water availability analysis, limited water was available for appropriation from August through the end of February, so biological flow recommendations were reduced.

40.0 cfs – April 1 through June 30

A flow rate of 40 cfs maximizes preferred habitat for adult Bluehead and Flannelmouth Suckers across both sites. This flow rate also maximizes preferred spawning habitat for these species. Preserving this flow rate during the spring runoff period (including the rising and receding limb of the hydrograph) will support native fish by providing optimal depth, velocity, and substrate conditions to enable spawning migrations, as well as optimal overall habitat conditions for adult species. The snowmelt runoff peak can occur anytime between April and June on Milk Creek and is critically important in cueing native fish species to spawn, as well as providing geomorphic functions that support life cycle requirements of these fish. The higher flow rate supports sediment mobilization in the stream which supports habitat diversity and healthy spawning beds by flushing fines from interstices to support clean cobble and gravel substrate in the channel (the preferred spawning substrate for these species). Higher flows also support recruitment of woody debris and organic materials that can facilitate healthy stream function as well as a robust macroinvertebrate food base for fish. Protecting this flow rate over this extended spring runoff time period will provide a ramp during and after peak flows that helps with drift, dispersal, and incubation of eggs in the channel.

8.0 cfs - July 1 through July 31

The SEFA fish passage evaluation showed that 8 cfs will preserve a pathway for fish that is at least 2 feet wide and 0.6 feet deep across all modeled cross-sections at both study sites. The recommended flow rate of 8 cfs will maintain longitudinal connectivity of habitat and will enable large-bodied adult fish to move throughout Milk Creek to find suitable habitat or to emigrate into the Yampa River without being stranded. Additionally, this flow rate will support larvae development and emergence by maintaining wetted area in the channel and channel margins. This flow rate will support both fish passage for all life stages of native fish and habitat for larvae development and young-of-the-year fish to grow and mature in channel margins, creating refuge habitat for larvae, young-of-the-year, and juvenile fish.

4.5 cfs – August 1 through September 30

This recommended flow rate is based on limited water availability during the late irrigation season. Despite low flow conditions and limited mobility between habitat types, native species will use available habitat within Milk Creek during this period. These low baseflows allow Bluehead Sucker stocked by CPW to acclimate to wild conditions. The SEFA model AWS versus discharge relationship shows that additional increments of flow provide significant habitat response benefits at flow rates below 10 cfs. Preserving this flow rate is important because it enables rearing of juvenile and young-of-the-year fish. Growth during this late summer period is critical to their survival over the winter period. There is reduced occupancy by non-native species and less competition foraging in Milk Creek than in the mainstem Yampa River.

5.2 cfs – October 1 through December 31

This recommended flow rate is based on limited water availability during the baseflow period. Baseflow during the winter months is necessary to provide enough habitat variety to overwinter resident native fish. Additionally, the SEFA model AWS versus discharge relationship shows that additional increments of flow provide significant habitat response benefits at flow rates below 10 cfs.

7.8 cfs – January 1 through February 29

This recommended flow rate is based on slight water availability limitations during the baseflow period. This flow rate will provide conditions to enable longitudinal movement of resident fish to find more advantageous habitat.

18.0 cfs - March 1 through March 31

A flow rate of 18 cfs will provide enabling conditions during the beginning of the spawning period for native fish, a critical period for completing their life cycle. As low elevation snowmelt runoff begins in the early part of spring, it is important to preserve flows that begin to cue native fish and allow longitudinal movement between habitat types in order to reach suitable spawning areas.

Summary and Conclusions

CPW and BLM have developed an ISF proposal that is both reasonable and protective of the natural environment in Milk Creek that supports the native Three Species. CPW participates in the ISF Program and develops ISF recommendations to address CPW's legislative directives "… 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" [§33-1-101 (1) C.R.S.], and "… that the natural, scenic, scientific, and outdoor recreation areas … 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 acquisition, development, and management of … lands, waters, and facilities.” [§33-10-101 (1) C.R.S.].

Thank you for the opportunity to submit this important flow recommendation for the Board’s consideration on lower Milk Creek. CPW staff will be available at the March Board meeting to answer any questions about the benefits this recommendation will provide for native species.

Sincerely,

Kathryn Birch

Katie Birch
CPW Instream Flow Program Coordinator


Macroinvertebrate Sampling in October 2023

Large hemipteran observed by CPW staff in October 2023


CPW electroshocking survey in October 2023

Milk Creek Fish Community and Movement Summary

Tyler Swarr
Native Aquatic Species Biologist
Northwest Region

Jenn Logan
Native Aquatic Species Manager

Since 2009, fishery surveys have been conducted by Colorado Parks and Wildlife (CPW) regularly at Milk Creek in the reaches above the confluence with the Yampa River. Much of the work has been conducted just downstream of Highway 13 on privately owned land and Bureau of Land Management (BLM) property. Data is limited for the reaches below Thornburgh to the confluence of the Yampa River prior to 2009. Native suckers are present throughout Milk Creek and have been documented since at least 1963. However, interest in the creek for fisheries purposes early on was limited to trout and very little work was conducted in the lower reaches due to high temperatures and turbidity that preclude trout populations.

Milk Creek serves as a source of native fish for the Yampa River basin. The creek's unique characteristics including high turbidity, warmer temperatures, low base flows, and sporadic high flow events (Figure 1), generally favor native fish species and provide spawning areas, refuge and nursery habitat. Historically, the primary inhabitants of lower Milk Creek (Flannelmouth Sucker, Bluehead Sucker and Roundtail Chub collectively known as "Three Species") are native non-listed species (not listed as endangered or threatened).

Population estimates of individual species are difficult at Milk Creek due to poor conditions for electrofishing. The stream has very high conductivity which affects the capture efficiency and provides poor confidence intervals for population estimates. Additionally, when the majority of native fish occupy the creek in the spring and early summer, high flows make collecting accurate population estimates challenging. Fishery surveys on the reaches of Milk Creek downstream of Highway 13 have been limited to presence/absence surveys only.

Because of the difficulty in collecting accurate and reliable population estimates for fish at Milk Creek, we rely heavily on Passive Integrated Transponder (PIT) tag antennas and PIT-tagged fish to inform the use of the creek. We track the movement of fish in and out of the creek using submersible 3-foot and 5-foot diameter PIT tag antennas (Figure 2). The antenna arrays detect individual PIT tags as a tagged fish swims over or near the antenna. Because of the limited read range, we deploy antennas in the thalweg, or deepest portion of the creek, whenever possible because this is where fish are most likely to concentrate as they migrate upstream and downstream. We typically deploy six antennas annually throughout the lower 6.5 miles of Milk Creek, which covers BLM land ownership near the confluence with the Yampa River and private lands towards Colorado Highway 13 (Figure 3). The submersible antennas are powered by lithium batteries which last for approximately 21 days. We change batteries as frequently as possible during antenna deployment to ensure continuous tag detections, however, occasionally an antenna battery may die one or two days before we are able to return and exchange the battery, so there are occasional gaps in our detection data.

Beginning in 2015, approximately 2,500 Bluehead Suckers are released annually in the lower 6 miles of Milk Creek as part of an effort to increase overall numbers of Bluehead Sucker in the Yampa River Basin. Milk Creek was identified as an augmentation site for native suckers due to few predators, low base flows that allow captive-reared fish to acclimate to wild conditions and a history of the species in the drainage. This was the first release of captive-reared Bluehead Sucker anywhere. The CPW Native Aquatic Species Restoration Facility in Alamosa, Colorado annually produces seven-inch long Bluehead Suckers for the Milk Creek augmentation project (Table 1). They also began to raise Flannelmouth Suckers in limited numbers in 2022 for the Milk Creek Project. Each spring, we PIT tag all of the fish that will be stocked into Milk Creek. The fish are then brought to Milk Creek by hatchery staff, typically in late April. Around the time of stocking, we see the number of unique tags detected daily in Milk Creek jump up substantially, as the fish begin to explore their new home (Figure 4). Other biologists and partner agencies also encounter stocked fish on the Yampa River, with many of the Milk Creek fish detected near Maybell, Colorado later in the year once they return to the Yampa River (Figure 5). Monitoring survival and movement of the stocked fish is conducted with a combination of surveys and submersible PIT tag antenna arrays.

Since 2009, surveys have captured 4 native fish species (Bluehead Sucker, Flannelmouth Sucker, Roundtail Chub, and Speckled Dace) and 13 non-native fish species in Milk Creek. All but 5 of the non-native fish species are small-bodied cyprinid (minnow) species. A few juvenile Smallmouth Bass and Green Sunfish have also been captured. No adult bass or sunfish have been encountered. All Smallmouth Bass captures occurred in the lower 2 miles and most likely emigrated from the Yampa River.

Species composition changes across seasons and is flow-dependent. Large adult suckers are most often found during high flows and spring runoff (Figure 6), likely seeking out spawning habitat. In late summer, during low flow periods, juvenile suckers and both native and non-native small-bodied minnows are frequent catches. During fall and winter, most native fish migrate from Milk Creek into the Yampa River where they overwinter. We also note that tagged fish move back into Milk Creek during monsoonal rains or discrete high-flow events in the creek, seemingly for refuge or to exploit newly available habitat (Figure 7). The data gathered since 2009 continues to provide valuable information in understanding the use and importance of tributaries by native fish in the Yampa River basin.

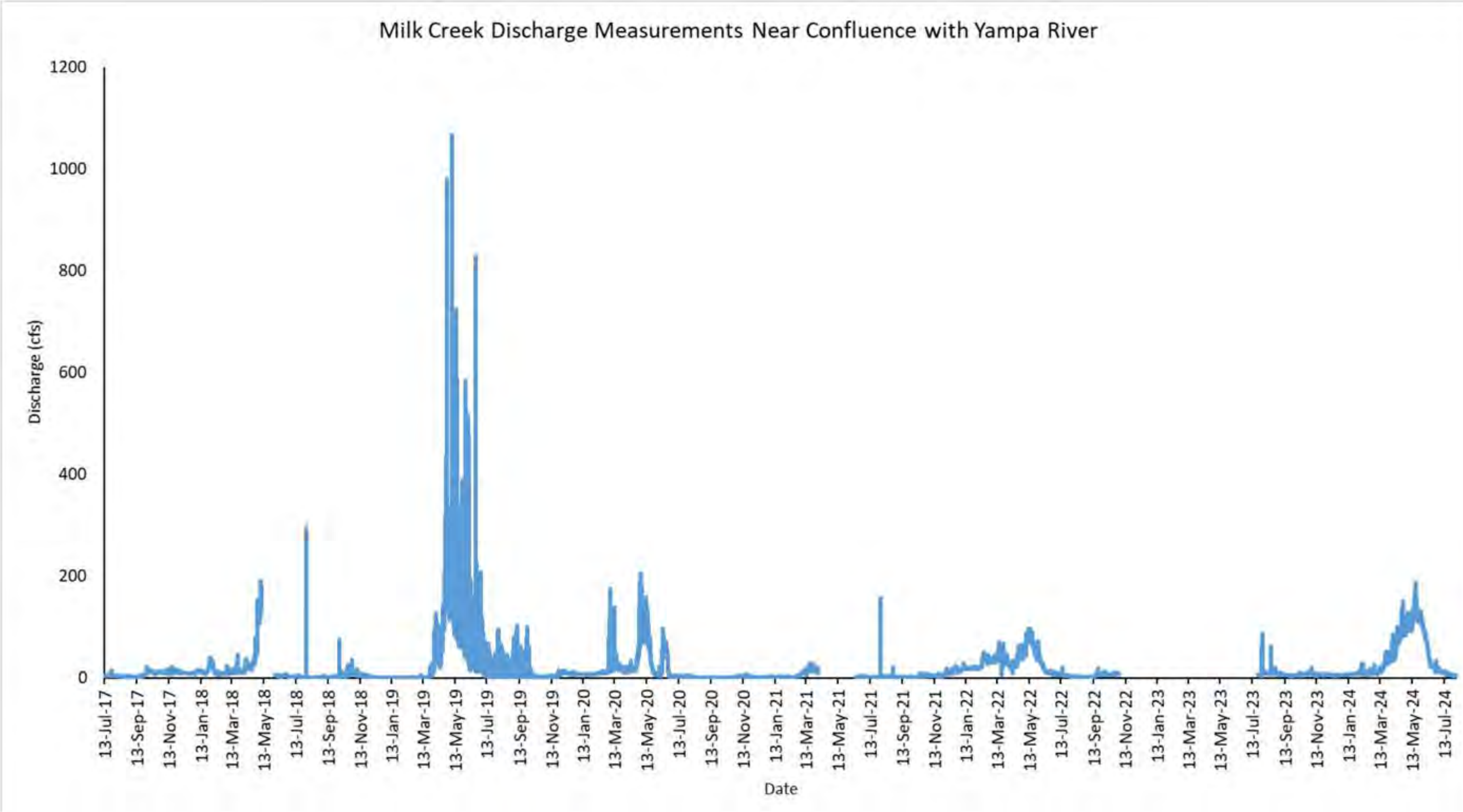


Figure 1. Stream discharge for Milk Creek near the confluence with the Yampa River from July 2017 through July 2024 (CWCB-gage records).

Figure 2. Photograph of a 3-foot diameter submersible PIT tag antenna. The circular tubing has a small copper wire inside of it which produces a low frequency electromagnetic field. When this field is disturbed by a PIT tag, the tag's unique alpha-numeric code is read and saved, along with the date and time of the detection by the datalogger on the antenna.

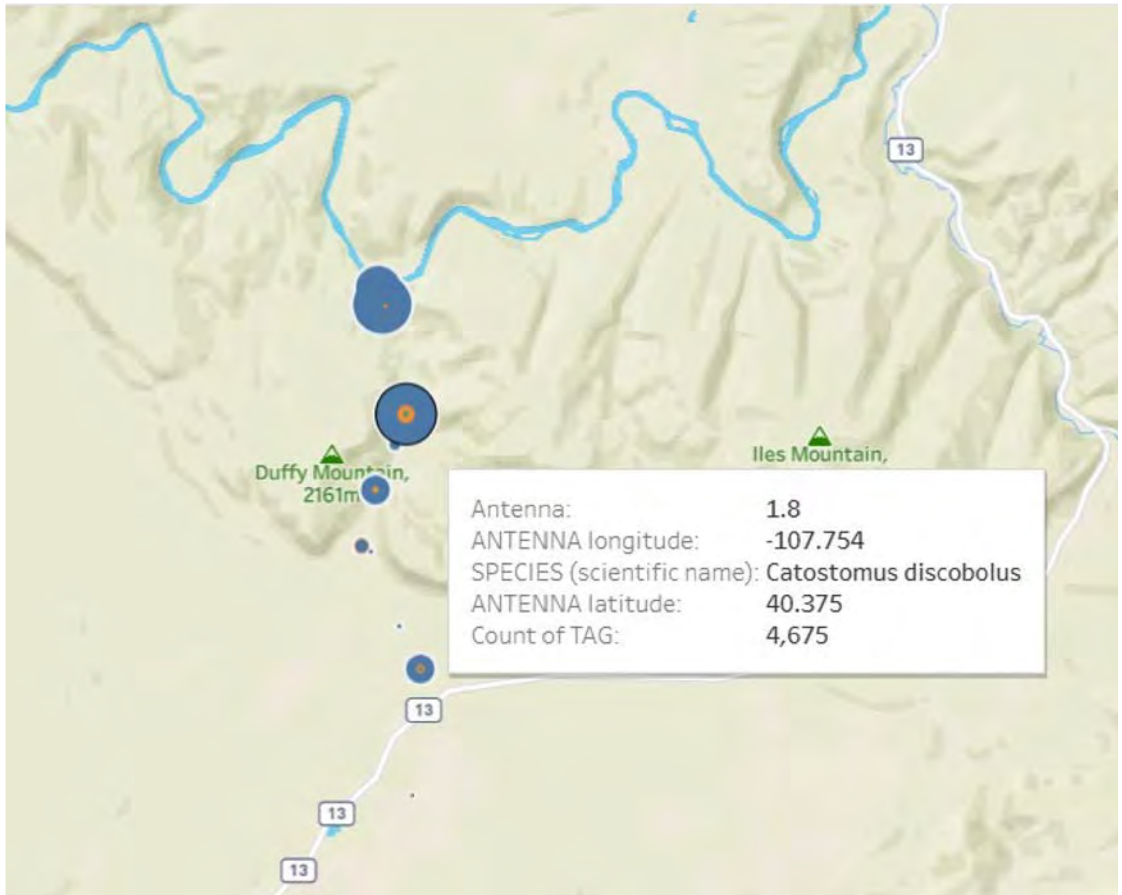


Figure 3. Map of Milk Creek showing the locations of PIT tag antennas with the relative number of tag detections by species from 2015 - summer 2024. Bluehead Sucker detections are in blue, while Flannelmouth Sucker detections are in orange. Larger circles indicate a higher number of individual fish detected at that antenna. Fish typically are detected on the antennas in the lower four miles of Milk Creek where the stream is confined by canyon walls. Antennas are named by the river mile they are placed at upstream of the confluence with the Yampa River.

Table 1. Bluehead Sucker and Flannelmouth Sucker numbers stocked into Milk Creek by Colorado Parks and Wildlife's Native Aquatic Species Restoration Facility (NASRF). All fish are raised to approximately 7 inches in total length before stocking.

	Number of Fish Stocked	
Year	Bluehead Sucker	Flannelmouth Sucker
2015	2,807	0
2016	2,493	0
2017	1,924	0
2018	2,491	0
2019	2,240	0
2020	0	0
2021	2,440	0
2022	2,206	343
2023	2,472	0
2024	1,876	3,206

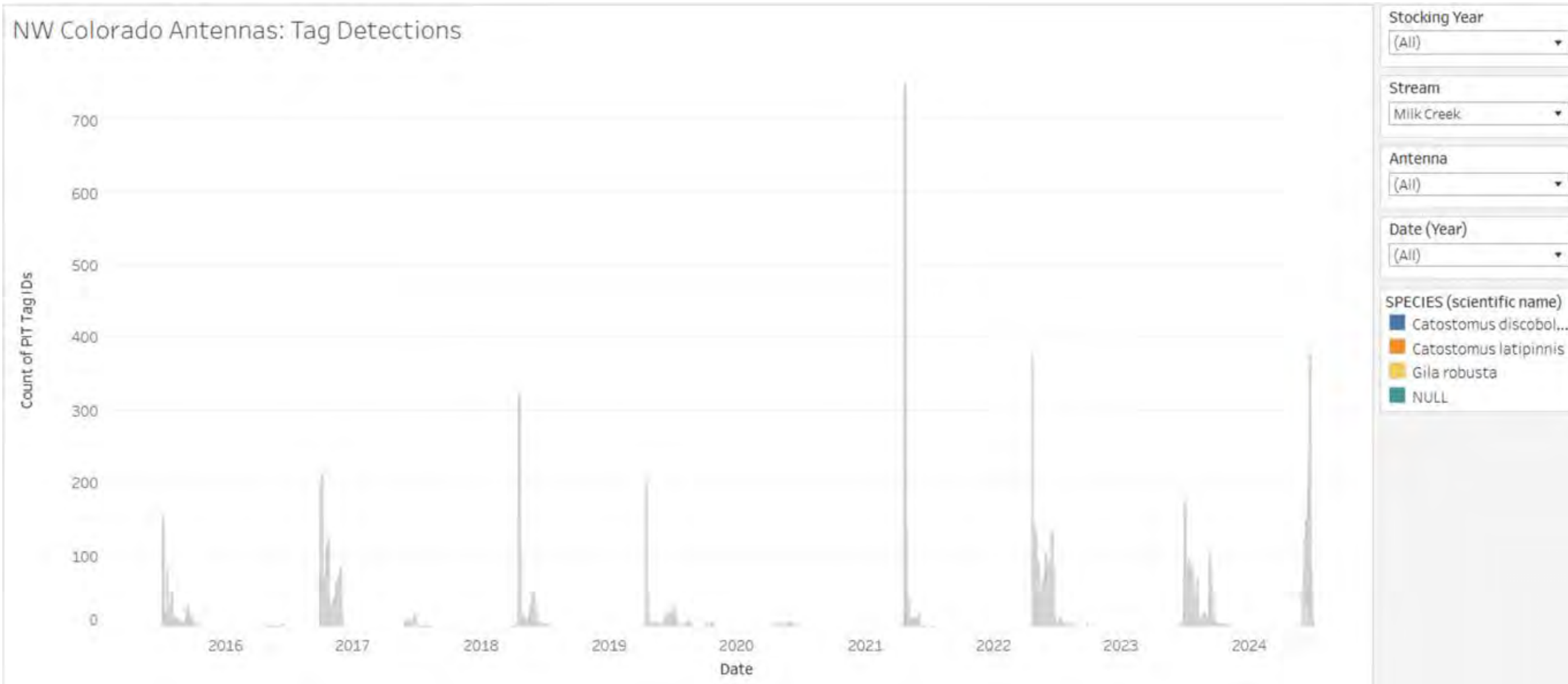


Figure 4. Graph showing the number of unique PIT tag numbers detected every day at Milk Creek from 2015 to 2024. The number of unique PIT tags detected per day is shown on the y-axis and the date is shown on the x-axis. The highest number of unique tags detected in one day occurred on April 21st 2021, which is one day following the 2021 Bluehead Sucker stocking event. Major spikes in detections typically occur immediately following the annual stocking event. No fish were stocked in 2020.

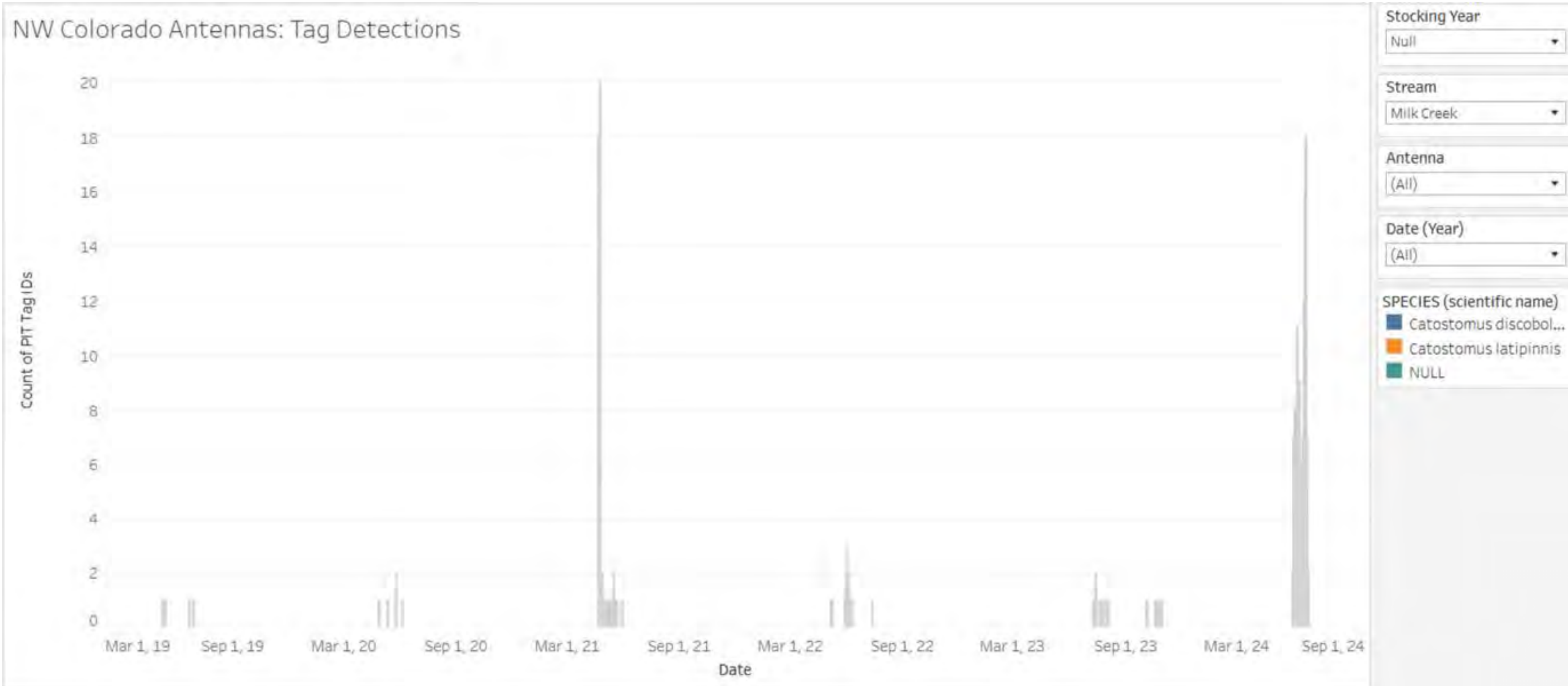


Figure 5. Unique PIT tag antenna detections of wild fish that are not hatchery-raised from 2019 - summer 2024. Biologists PIT tag most of the wild native fish species they encounter throughout the Yampa River Basin, so there are wild fish with PIT tags in the Yampa River drainage that we occasionally detect with our antenna arrays in Milk Creek.

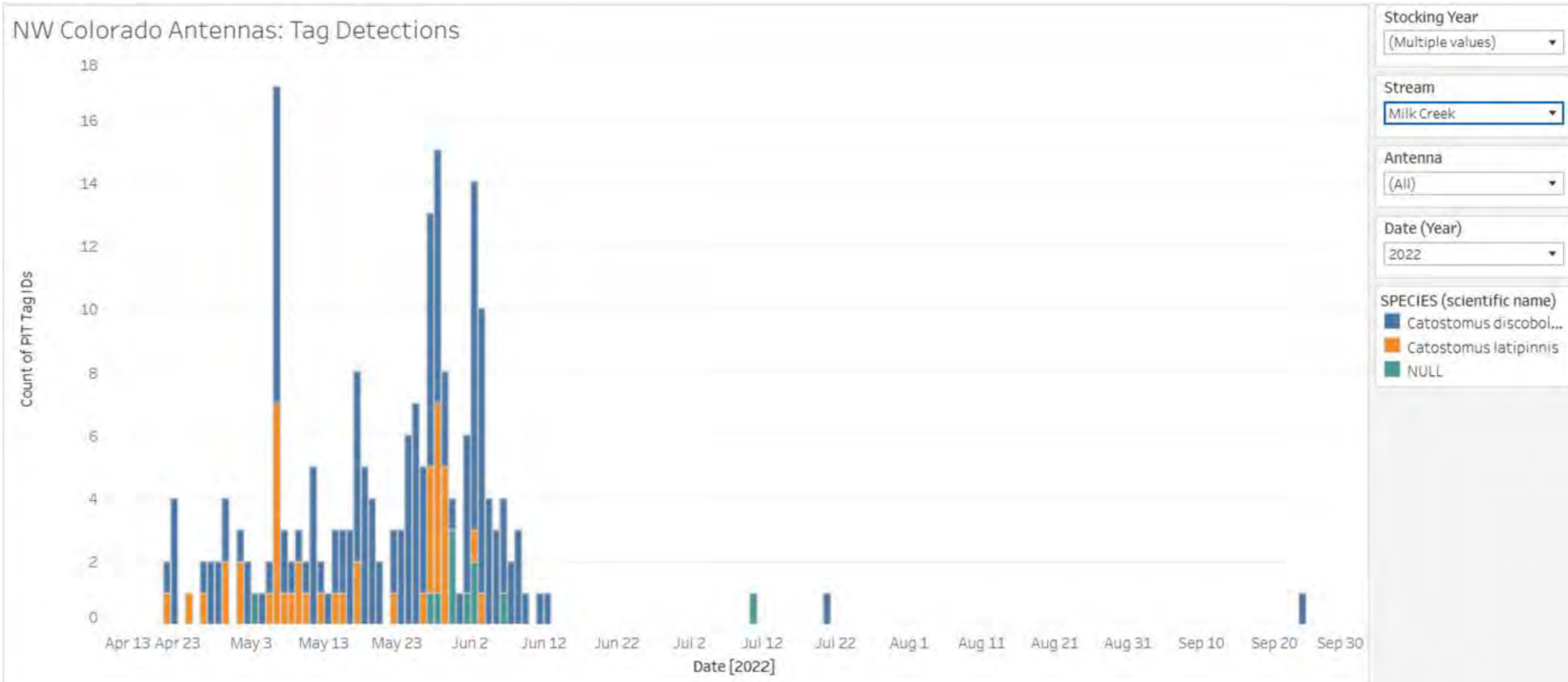


Figure 6. Unique PIT tag antenna detections from 2022 not including the fish stocked in 2022. This figure shows the timing of fish returning to Milk Creek during the rising limb of the hydrograph and gives the reader an approximation of the survivorship and site fidelity to Milk Creek of previously stocked fish. Adult fish leave Milk Creek after runoff and only occasionally return later in the year. NULL tags (teal) are fish that were detected but their identity has not yet been entered into the PIT tag database. These NULL tags are most likely wild fish that other biologists tagged somewhere in the basin. Catostomus discobolus (blue) are stocked Bluehead Sucker. Catostomus latipinnis (yellow) are stocked Flannelmouth Sucker.

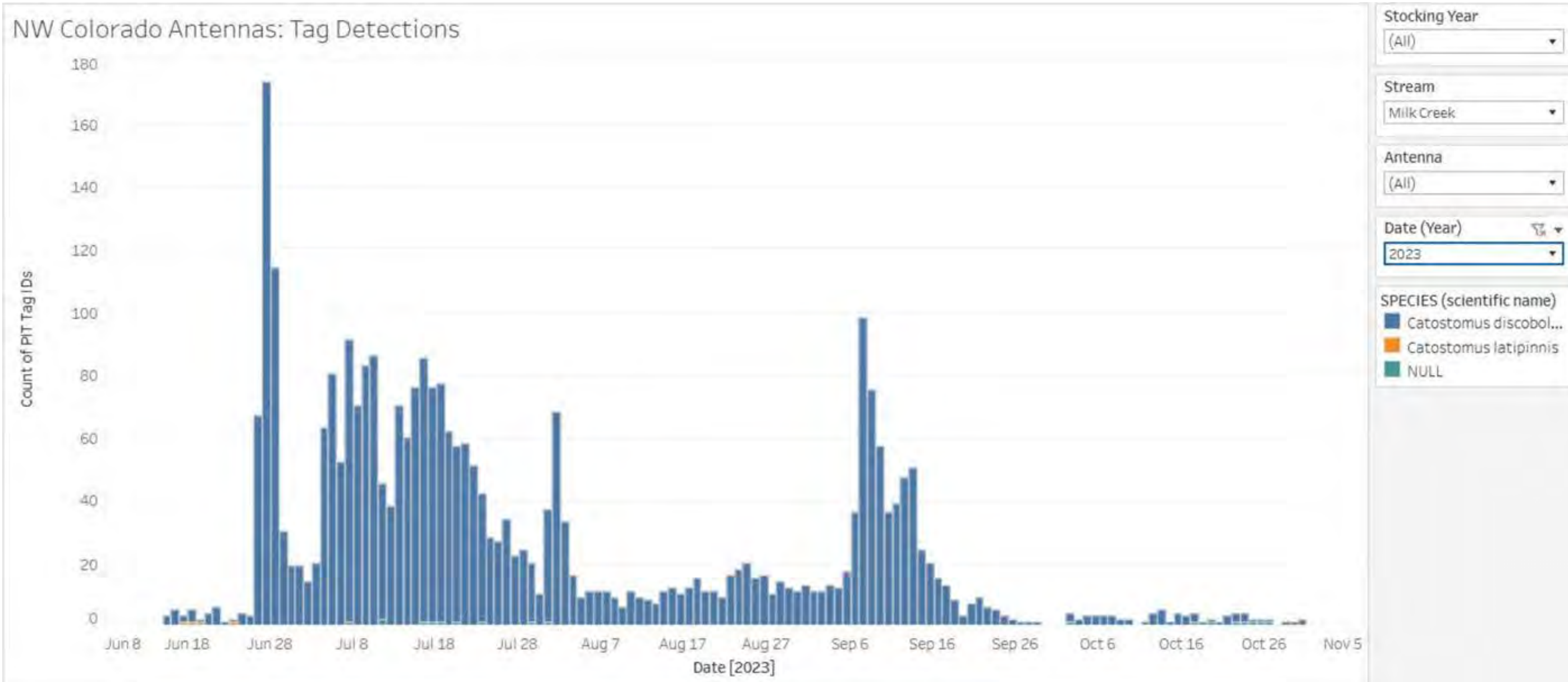


Figure 7. Annual tag detection histogram for Milk Creek showing the number of unique tags detected per day on the y-axis and the date on the x-axis for 2023 as an example of summer and fall detections. PIT tag antennas were deployed in June of 2023 and removed at the end of October once winter conditions became likely. Bluehead Suckers were stocked on June 26th 2023. A monsoon event occurred in September 2023, which triggered many of the fish to move back into Milk Creek during this high-flow event. Newly stocked juvenile fish remain in the creek throughout most of the year and leave Milk Creek for the mainstem Yampa River once baseflow conditions in Milk Creek set in around late September.

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
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James F. Karpowitz
Director

Publication Number 06-18
September 2006

Revised 2019
Rangewide Conservation Team

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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 flannelmouth 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 flannelmouth 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, flannelmouth sucker and bluehead sucker populations sufficient to ensure persistence of each species within their ranges.

    1) Establish measurable criteria to evaluate the number of populations required to maintain the three species throughout their respective ranges.

    2) Establish measurable 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 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.

IV. OTHER SPECIES INVOLVED

This Agreement is primarily designed to ensure the persistence of roundtail chub, bluehead sucker, and flannelmouth 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 woodhousii),* 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

02/23/04

Duane L. Shroufe — Date
Director

Colorado Division of Wildlife
6060 Broadway
Denver, Colorado 80216

3/22/04

for Russell George — Date
Director

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

3/5/04

for: Terry Crawforth — Date
Director

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

4-15-04

Bruce Thompson — Date
Director

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

2/4/04
Kevin K. Conway Date
Director

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

for 3-12-04
Terry Cleveland Date
Director

3/11/04
Ron Arnold Date
Chief Fiscal Officer

Approval as to form:

3/11/04
Ted Preston Date
Assistant Attorney General

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.

Alan L Kesterke
____
Bureau of Land Management
Wyoming State Office

April 8, 2005
____
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.

Sally Wisely

Bureau of Land Management
Utah State Office

5/16/05

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

4/7/06
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 7/5/05
Michael D. Snyder — Date
Acting Director

The U.S. Bureau of Reclamation, Upper Colorado Region (Reclamation), hereby states its support of the goals, objectives, and actions of the Range-Wide Conservation Agreement for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker (Utah Division of Wildlife Resources publication no. 06-18).

Financial support of any activity prescribed to the signatories of the Conservation Agreement is not guaranteed and is contingent upon Reclamation's authority and adequate funds being made available and allocated to Reclamation.

Reclamation recognizes that implementation of certain conservation actions identified in the Conservation Agreement are directed toward the state signatories.

Acting for

Rick L. Gold
Regional Director

4/3/07
Date

CONSERVATION COMMITMENT

The U.S. Fish and Wildlife Service, Mountain-Prairie Region, hereby states its intent and commitment to assist with and participate in the support of the Range-wide Conservation agreement and strategy for roundtail chub *Gila robusta*, bluehead sucker *Catostomus discobolus*, and flannelmouth sucker *Catostomus latipinnis*, as prepared for the Colorado River Fish and Wildlife Council. Specific involvement may include:

1. Providing representation to the Three Species Conservation Team.

2. Consistent with applicable laws and procedures, funding for eligible projects through the State Wildlife Grant program as long as State matching funds are available and projects are consistent with the State Wildlife Plan.

3. Providing comments under existing laws and regulations for any projects federally authorized, funded, or carried out that may impact any of the three species.

4. Using the Service's authority under the Fish and Wildlife Act of 1956 (16 U.S.C. 742a-742j), as amended, and the Migratory Bird Hunting Stamp Act (16 USC .718), to protect the three species from land and water altering activities, on National Wildlife Refuge System lands.

Performance of all activities listed above is contingent upon the annual receipt of adequate funding. This commitment shall not prohibit the signatory agency from engaging in management actions regarding three species conservation beyond those described in this commitment page and in the associated Plan. Such management actions should be coordinated with the Three Species Conservation Team.

This commitment shall become effective on the date of signature by the participating party and shall remain in effect until the signatory party chooses to terminate the commitment or until the Three Species Conservation Team decides (by consensus) to terminate the Plan. The signatory party will provide 90 days written notification to the other parties upon deciding to terminate involvement.

The U.S. Fish and Wildlife Service has the authority to enter into this commitment through the Endangered Species Act of 1973, as amended; the Fish and Wildlife Act of 1956, as amended; the Fish and Wildlife Coordination Act, as amended; and 43 CFR part 24, U.S. Department of Interior's fish and wildlife policy on State and Federal relationships.

By signing the document below, the Service acknowledges that it is also signing as a party and participant to the whole of the 2006 Three Species Conservation and Management Plan attached hereto.

Mitch King, Regional Director
U.S. Fish & Wildlife Service, Mountain-Prairie Region

12-28-06
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 January2004 ("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

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
____
Sally Wisely
State Director
Bureau of Land Management
Colorado State Office

10/4/07
____
Date

-Signature Page-

This signature page is an appendix to the Range-Wide Conservation Agreement for Roundtail Chub, Bluehead Sucker, and Flannelmouth Sucker dated September, 2006 ("Agreement").

The Southern Ute Indian Tribe enters this Agreement subject to the following conditions:

- Nothing in this Agreement provides a basis for requiring the Southern Ute Indian Tribe to comply with state law.
- Nothing in this Agreement diminishes the jurisdiction of the Southern Ute Indian Tribe, including its legislative, regulatory, and judicial jurisdiction.
- Nothing in this Agreement waives the sovereign immunity of the Southern Ute Indian Tribe
- Nothing in this Agreement shall operate as a bar, constitute a waiver of any rights of the Tribe, or in any respect affect the ability of the Tribe to pursue other objectives, besides conservation of native fish species, in connection with the use of its water resources, including economic objectives.

SOUTHERN UTE INDIAN TRIBE

By: Clement J. Frost
Clement J. Frost, Chairman
Southern Ute Indian Tribal Council

Sept. 06, 2007
Date

Southern Ute Indian Tribe
P.O. Box 737
Ignacio, CO 81137

CONSERVATION COMMITMENT

The U.S. Fish and Wildlife Service (Service), Region 2, hereby states its intent and commitment to assist with and participate in the implementation of the Range-Wide Conservation Agreement and Strategy for Roundtail Chub (*Gila robusta*), Bluehead Sucker (*Catostomus discobolus*), and Flannelmouth Sucker (*Catostomus latipinnis*). Specific commitments made hereby are as follows:

1. To provide a representative to the Range-Wide Coordination Team, which is comprised of all signatories.

2. Consistent with applicable laws and procedures, provide funding through the State Wildlife Grant Program for State selected projects that are consistent with the applicable State Wildlife Action Plans.

3. To review and provide comments under existing laws and regulations for any projects federally authorized, funded, or carried out that may impact any of the three species.

4. To use the Service's authority under the Fish and Wildlife Act of 1956 (16 U.S.C. 742a-742j), as amended, the Migratory Bird Hunting Stamp Act (16 USC .718), and the.Fish and Wildlife Coordination Act of 1934, as amended, to protect the three species from land- and water-altering activities, on National Wildlife Refuge System lands.

5. With regard to arbitration in the state of Arizona: If required by law, the Parties agree to engage in alternative dispute resolution procedures authorized by their statutes, regulations, and court rules, including but not limited to 5 U.S.C. § 575 and A.R.S. § 12-1518.

Performance of all activities listed above is contingent upon the annual receipt of adequate funding. This commitment shall not prohibit the signatory agency from engaging in management actions beyond those described in this commitment page and in the associated Plan. Such management actions should be coordinated with the Range-Wide Coordination Team.

This commitment shall become effective on the date of signature by the participating party and shall remain in effect until the signatory party chooses to terminate the commitment or until the Range-Wide Coordination Team decides (by consensus) to terminate the Plan. The signatory party will provide 60 days written notification to the other parties upon deciding to terminate involvement.

The Service has the authority to enter into this commitment through the Endangered Species Act of 1973, as amended; the Fish and Wildlife Act of 1956, as amended; the Fish and Wildlife Coordination Act of 1934, as amended; and 43 CFR part 24, U.S. Department of the Interior's fish and wildlife policy on state and federal relationships.

for Benjamin N. Tuggle, Regional Director
U.S. Fish and Wildlife Service, Region 2

8/13/07
Date

CONSERVATION COMMITMENT

The U.S. Forest Service, Intermountain Region, and the Ashley, Manti-La Sal, Uinta-Wasatch-Cache, Bridger-Teton, Caribou-Targhee, and Sawtooth National Forests (Forest Service), hereby state their intent and commitment to assist with and participate in the implementation of the Rangewide Conservation Agreement and Strategy for Three Fish Species, as prepared by the interagency Three Species Conservation Team. Specific commitments made hereby are as follows:

1. To provide representation to the Three Species Conservation Team, this is comprised of all signatory agencies.

2. To work in cooperation with the Three Species Conservation Team to conduct surveys and conservation actions in historical and suitable habitats within the Ashley, Manti-La Sal, Uinta-Wasatch-Cache, Bridger-Teton, Caribou-Targhee, and Sawtooth National Forests and to assist with regular status assessments of all known populations on these National Forests.

3. To consider possible impacts (both positive and negative) of forest management decisions and plans on the three species and their habitats and to take measures to avoid and/or mitigate such impacts, if thought to be detrimental, whenever possible within constraints of Forest Service policy and regulations.

Performance of all activities listed above is contingent upon the annual receipt of adequate funding. This commitment shall not prohibit the signatory agency from engaging in management actions regarding three species conservation beyond those described in this commitment page and in the associated Strategy. Such management actions should be coordinated with the Three Species Conservation Team.

This commitment shall become effective on the date of signature by the participating party and shall remain in effect until the signatory party chooses to terminate the commitment or until the Three Species Conservation Team decides (by consensus) to terminate the plan. The signatory party will provide 90 days written notification to the other parties upon deciding to terminate involvement.

The U.S. Forest Service, Intermountain Region, is granted authority to enter into this commitment through the National Forest Management Act of 1976 and the Sikes Act of 1960.

By signing the document below, the Forest Service acknowledges that it is also signing as a party and participant to the whole of the Rangewide Conservation Agreement and Strategy for Three Fish Species attached hereto.

Harv Forsgren — 2/9/2011

HARV FORSGREN, Regional Forester
United States Forest Service, Intermountain Region

Date

RANGE-WIDE CONSERVATION AGREEMENT FOR ROUNDTAIL CHUB, BLUEHEAD SUCKER, AND FLANNELMOUTH SUCKER
IDAHO DEPARTMENT OF FISH AND GAME

The Idaho Department of Fish and Game (IDFG) hereby states its intent and commitment to assist with, participate in, and implement the Range-wide Conservation Agreement and Strategy for Roundtail Chub *Gila robusta*, Bluehead Sucker *Catostomus discobolus*, and Flannelmouth Sucker *Catostomus latipinnus*, as prepared by the Range-wide Coordination Team. Idaho Code Section 36-104(b)(9) authorizes the IDFG to "enter into cooperative agreements with state and federal agencies, municipalities, corporations, organized groups of landowners, associations, and individuals for the development of wildlife rearing, propagating, management, protection, and demonstration projects." Bluehead sucker are a native species in Idaho found in the upper Snake River and Bear River basins. Specific commitments are as follows:

1. To provide a representative to the Range-wide Coordination Team, which is made up of representatives from various agencies listed in the Agreement, to implement conservation elements described in the Strategy.
2. To assume responsibility for the inventory and monitoring of bluehead sucker populations in the State of Idaho and to annually compile and report inventory and monitoring information and provide such information to all participating agencies and parties.
3. To implement and enforce specific State statutes and fish and game codes (Fish and Game Code of Idaho) that protects and prohibits the collection and/or importation of threatened, endangered and protected species, including bluehead sucker.
4. To continue to conduct and support research to collect information on biotic and abiotic limiting factors of bluehead sucker populations, habitat and ecology and to work to reduce or eliminate limiting factors.

Performance of activities above is contingent on adequate funds being made available and allocated to the IDFG. This Agreement shall not prohibit the IDFG engaging in management actions regarding bluehead sucker conservation beyond those described in this Agreement and Strategy. Such management actions will be coordinated with the Range-wide Coordination Team and other appropriate parties as deemed necessary.

This Agreement shall become effective on the date of signature by the IDFG, and shall remain in effect until the IDFG chooses to withdraw from the Agreement in whole or in part, or the Agreement is terminated by consent of the Range-wide Coordination Team. Either the IDFG or the Range-wide Coordination Team may terminate the Agreement by providing 90 days written notification to the other party.

By signing the document below, the IDFG acknowledges that it is also signing as a party and participant to the whole of the Range-wide Agreement and Conservation Strategy attached hereto.

J M Unsworth for — 5/6/11

Virgil Moore, Director — Date
Idaho Department of Fish and Game

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*[1]), bluehead sucker (Catostomidae: *Catostomus discobolus*), and flannelmouth 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 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 Endangered Species Act of 1973, as amended (ESA).

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[1] Includes the formerly recognized headwater chub (G. nigra) and Gila chub (G. intermedia) in the lower Colorado basin (Page et. al. 2017).

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. Tributaries of the Colorado River in Arizona are the Little Colorado and Gila rivers and the Virgin River 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 occur in the CRB, the Upper Snake River Basin, and the Bonneville Basin. Recent genetic research and literature has suggested that Bluehead Sucker populations in the Bonneville and Upper Snake basins are genetically distinct from Bluehead Sucker populations in the CRB (Hopken et al. 2013; Smith et al. 2013; Unmack et al. 2014), however these distinct groups are still considered one species within this agreement.

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 for roundtail chub, bluehead sucker, and flannelmouth sucker.

Roundtail Chub

Roundtail chub are found in the mainstem of major rivers, smaller tributary streams, and, to a more limited extent, lake habitats. The species utilizes a variety of substrate types (silt, sand, gravel and rocks) and prefer murky water to clear (Sigler and Sigler 1996, Brouder et al. 2000, Bower et al. 2008, Bottcher 2009). 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).

In lotic environments, 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, Bower et al. 2008). 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). Within the few lakes where they are found, Roundtail Chub utilize littoral areas. Substrate does not appear to be an important factor in lentic habitat selection, however, cover in the form of aquatic vegetation is often selected for (Laske 2010).

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, data from the Upper Basin in Wyoming indicates that roundtail chub may mature at sizes as small as 142 mm (Peter Cavalli 2004 personal communication, Compton 2007). 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 vegetation, aquatic and terrestrial insects, fish, snails, crustaceans, algae, and occasionally lizards (Sigler and Sigler 1996, Osmundson 1999, Bestgen 2000, Brouder 2001, Laske 2010).

Bluehead Sucker

Bluehead sucker tend to utilize swifter velocity, higher gradient habitats than those occupied by either flannelmouth sucker or roundtail chub. These fish are found in warm to cool streams (20 °C) with rocky substrates (Sigler and Sigler 1996, Bestgen 2000, Sweet 2007, Banks 2009). 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, runs or pools, further away from shore, and cover and rocky substrate (Childs et al. 1998, Sweet 2007, Banks 2009, Hines 2013).

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 sexual maturity is achieved at highly variable sizes and ages across the native range. Compton (2007) found mature fish at two years of age and/or at 127 to 179 mm in length in a small southern Wyoming stream. Smith (1966) reported fish < 100 mm SL exhibiting sexual maturity in smaller streams, but also reported minimum sizes of sexually mature fish from larger rivers of > 245 mm SL. Bluehead suckers participating in a major spawning migration from the Gunnison River were > 240 mm TL (Hooley-Underwood et al. 2019). Time of spawning varies by elevation, occurring during the 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, Sweet 2007). 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). After hatching, larval fish drift downstream and seek out near-shore, slow-velocity habitats (Robinson et al. 1998).

Flannelmouth Sucker

Flannelmouth sucker reside in mainstem and tributary streams, and occasionally lakes. Elements of flannelmouth 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, Sweet 2007, Banks 2009). Substrates utilized consist of gravel, rock, sand, or mud (McAda 1977, Sigler and Sigler 1996, Sweet 2007, Banks 2009). Flannelmouth 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 flannelmouth 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 flannelmouth sucker populations historically (Baxter and Stone 1995; P. Cavalli, Wyoming Game and Fish Department, 2004 personal communication). Flannelmouth 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).

Flannelmouth suckers have been documented to mature at four to five years of age and a minimum TL of 254mm in a small southern Wyoming stream (Compton 2007). In larger streams of the UCRB, fish reached maturity at age 4 to age 6 and at lengths exceeding 391 mm (McAda and Wydoski 1985). Recent studies of a spawning population in the Gunnison River basin showed that most spawning fish exceeded 400 mm TL, but some mature males were as small as 340 mm (Hooley-Underwood et al. 2019). 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 1977, Sigler and Sigler 1996, Sweet 2007, Hooley-Underwood et al. 2019). McKinney et al. (1999) (see also Chart 1987, Chart and Bergersen 1987) 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 accorded 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, hybridization with roundtail has been documented (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). 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 the Rio Nutria, tributary to the Little Colorado River in New Mexico (Turner and Wilson 2009). However, nearby populations of Zuni Bluehead Sucker exhibit very few alleles that can be attributed to *C. plebius*. Continued genetic investigations into the relationship between Zuni bluehead sucker and other bluehead suckers is needed.

It is well documented that both indigenous bluehead and flannelmouth sucker currently hybridize with invasive white sucker (*Catostomus commersoni*) throughout their range (Douglas and Douglas 2003, Douglas and Douglas 2008a and 2008b, Douglas et. al 2008, Mandeville 2015). Hybrids between flannelmouth and bluehead sucker have also been found but are rare (Hubbs et al. 1943, McDonald et. al 2008, Thompson and Hooley-Underwood 2019). Douglas and Douglas (2003) and McDonald et. al (2008) 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. In addition to hybridization between these indigenous suckers and non-native white sucker, hybridization between flannelmouth sucker and Utah sucker and bluehead sucker and longnose sucker have also been reported (Douglas and Douglas 2008a and 2008b, Mandeville 2015).

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). 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**,** connectivity, and flow regimes. Chemical characteristics may include (but are not limited to) 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 Service Plan Standards and Guidelines, National Park Service Natural Resources Management Guidelines, Bureau of Land Management (BLM) Properly Functioning Condition (PFC) protocols, and recommendations from related broad-scale assessments.

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 and other research institutions can aid in identifying habitat requirements for main channel three species populations and select tributary populations (e.g., Chart and Lenstch 1999, Trammell et al. 1999, Muth et al. 2000, Osmundson 1999, Tyus and Saunders 2001, McAda 2003, Sweet 2007, Banks 2009). 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 can be modeled as a function of stream discharge (Stewart et al. 2005, Anderson and Stewart 2007, Stewart and Anderson 2007). These investigators sought to derive biologically based instream flow recommendations for non-endangered native fish, which makes the study relevant 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 2-D allows for greater accuracy in habitat quantification. The 2-D approach 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 [USFWS] 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 June Sucker Recovery Implementation Program (USFWS 1999), the San Juan River Basin Recovery Implementation Program (SJRIP) (SJRIP, 1995), the Upper Colorado River Endangered Fish Recovery Program (UCREFRP) (USFWS 2003b), and the Virgin River Resource Management and Recovery Program (USFWS 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; Lentsch 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 and procedures can be found for Arizona (AZDGF 2011), Colorado (UCREFRP 2002; Martinez and Nibbelink 2004), New Mexico (NMDGF 2016), and Utah (Holden et al. 1996; UCREFRP 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, is it recognized that additional information will be acquired over the course of the Agreement that will allow adaptive approaches 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 1983; 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. 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 USFWS 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 USFWS has scientifically developed intercross policy concepts in completing their 12-month finding for westslope cutthroat trout (WCT) (USFWS 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 USFWS 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 USFWS 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 USFWS 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 (Lentsch 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

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 (Jordan and Evermann 1896, Sigler and Miller 1963, Minckley 1973). There have been no range-wide distribution or status assessments for any of these three species preceding the review of Bezzerides and Bestgen (2002), which concludes that distributions of all three fish species have contracted 50%, on average, from their historic distributions. A rangewide database is currently being developed and will provide reference for current and historical distribution of all three species.

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 (Bezzerides and Bestgen 2002). Data on smaller tributary systems are largely unavailable, and population abundance estimates are available only for short, isolated river reaches (Bezzerides and Bestgen 2002). In the lower CRB, roundtail chub distribution . 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 measurable criteria to evaluate the number of populations necessary to maintain the three species throughout their respective ranges.
    2) Establish measurable 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 rangewide database of current and historic information on roundtail chub, bluehead sucker, and flannelmouth sucker.
    - Complete annual updates to the database to reflect current 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.
    - 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) Maintain diversity of roundtail chub, bluehead sucker, and flannelmouth sucker populations.

- Genetically and morphologically characterize populations of roundtail chub, bluehead sucker, and flannelmouth sucker.
- Assess needs for additional population characterization.
- Apply new information to management strategies.

5) Maintain or, wherever possible, expand roundtail chub, bluehead sucker, and flannelmouth sucker distribution and abundance.

- Assure regulatory protection for three species is adequate within the signatory states.
- Maintain and expand roundtail chub, bluehead sucker, and flannelmouth sucker population distributions through transplant, augmentation, or reintroduction activities as warranted.

6) Maintain, enhance, and evaluate 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.

- Implement regulatory mechanisms for the long-term protection of habitat (e.g., conservation easements, water rights).

7) Address (as feasible and where possible) threats posed by nonnative species that compete with, prey upon, or hybridize with roundtail chub, bluehead sucker, or flannelmouth sucker.

   - Determine where detrimental interactions occur between the subject species and sympatric nonnative species.
   - Control detrimental nonnative species where necessary and feasible.
   - Evaluate effectiveness of nonnative control efforts.

8) Establish and implement long-term population monitoring programs for roundtail chub, bluehead sucker, and flannelmouth sucker.

   - Develop and implement monitoring programs for the subject species.
   - Evaluate current conditions of populations.

9) Implement outreach activities (e.g., development of partnerships, information and education activities) regarding conservation and management of roundtail chub, bluehead sucker, and flannelmouth sucker.

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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).

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

- **<u>ARBITRATION</u>: 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.**

- **<u>CANCELLATION</u>: All parties are hereby put on notice that this agreement is subject to cancellation pursuant to A.R.S. § 38-511.**

- **<u>OPEN RECORDS:</u> 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.**

Final
Milk Creek Instream Flow Study Report

Prepared for:
Colorado Water Conservation Board
Denver, Colorado

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September 30, 2024

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Introduction

Milk Creek is a tributary to the Yampa River downstream of the city of Craig, Colorado. Milk Creek is the largest tributary to the Yampa River between the confluence of the Williams Fork and Little Snake Rivers. Research and monitoring studies have shown that tributary streams in the upper Colorado and San Juan river basins provide important seasonal and year round habitat for native species, especially for native sucker species (Cathcart et al. 2015, Thompson and Hooley-Underwood 2019). Milk Creek provides spawning habitat for native Flannelmouth Sucker (*Catostomus latipinnis*) and Bluehead Sucker (*Catostomus discobolus*). Colorado Parks and Wildlife (CPW) and the Bureau of Land Management (BLM) are developing an instream flow recommendation for the Colorado Water Conservation Board (CWCB) to protect the lower 4 miles of Milk Creek.

The purpose of this study is to quantify hydraulic habitat in lower Milk Creek for the adult and spawning life stages of the two native suckers. The objective of the study is to determine the appropriate instream flows to protect native sucker habitat. Freshwater Consulting was contracted to provide field and technical training to CPW, BLM and CWCB staff necessary to complete flow and habitat modeling using the System for Environmental Flow Analysis (SEFA). Freshwater Consulting summarized the study and findings in this report. CPW, BLM, and CWCB staff assisted in collecting field data and processing data in SEFA.

Study Area

The study area extends from the Yampa River confluence upstream approximately 4 miles. The Milk Creek study sites are located approximately 0.5 miles and 0.9 miles upstream from the confluence of Milk Creek and the Yampa River (Figure 1). The entire 4-mile study area was evaluated prior to the site selection. The two study locations were selected as representative of the habitat within the lower 4 miles of Milk Creek. The overall gradient in the lower 4 miles of Milk Creek is 0.0052 ft/ft. The gradient for Site 1 is 0.0050 ft/ft and the gradient for Site 2 is 0.0057ft/ft and are generally similar to the overall gradient for the entire 4-mile reach. Both sites include all habitat types present within the study area. Habitat features in the reach include riffle, run and pool habitat with stream substrates that range in size from fine silt to large cobble. Both sites have multiple repeats of these habitat types and are representative of the overall reach habitat characteristics.

Species of Interest

Milk Creek provides habitat for Flannelmouth Sucker and Bluehead Sucker, which are endemic to the rivers in the Colorado River basin. BLM and CPW have signed a conservation agreement designed to protect and enhance habitat for these species. The agreement is titled “Range Wide Conservation Agreement and Strategy for Roundtail Chub (Gila robusta), Bluehead Sucker (Catostomus discobolus) and Flannelmouth Sucker (Catostomus latipinnis) 2006”. This document is also known as the “Three Species Agreement”. A priority conservation action in this agreement is the establishment of instream flow protection for streams known to provide habitat for the species.

Figure 1. Milk Creek Study Sites (Source: Google Earth).

Flannelmouth Sucker were historically widely distributed through the Upper Colorado River Basin and use mainstem rivers and tributary streams during their life cycle. Flannelmouth Sucker are a long-lived species with a maximum life span of about 30 years (Scoppettone 1988, Minckley 1991). Average size of mature adult Flannelmouth Suckers is approximately 500 mm (19.7 inches) (McCada 1977). Flannelmouth Sucker typically spawn between April and June in the upper Colorado River Basin (McAda 1977, Snyder and Muth 1990, Tyus and Karp 1990). Flannelmouth Sucker may reach sexual maturity by age 4 but most reach maturity by age 5 or 6 (McAda and Wydoski 1985). McAda (1977) reported spawning at water temperatures from 6 to 12 C. Flannelmouth Sucker eggs are demersal and adhere to the substrate. Eggs hatch in six to seven days (Carlson et al. 1979). Ripe Flannelmouth Sucker were collected by McAda and Wydoski (1985) in areas with cobble substrate and an average velocity of 3.3 feet per second (fps). Newly hatched Flannelmouth Sucker larvae drift with the river current as they absorb their yolk sac and become free swimming. The downstream drift of the larval life stage requires upstream movement of Flannelmouth Suckers as they mature to maintain populations throughout the rivers and streams.

Bluehead Sucker were historically distributed throughout the Upper Colorado River Basin similar to the distribution of Flannelmouth Sucker (Bezzerides and Bestgen 2002). Bluehead Sucker are a long-lived species with maximum ages reported at over 20 years (Scoppettone 1988, Minckley 1991). The majority of Bluehead Suckers are mature by the time they reach a total length of 380mm (15 inches) (McAda and Wydoski 1983). Spawning generally occurs in the spring and early summer from May through July (Holden 1973). Vanicek (1967) reported collecting ripe Bluehead Sucker in June and July in areas with large cobble.

Feeding habits differ between Flannelmouth Sucker and Bluehead Sucker. Both species are omnivorous and feed on algae and invertebrates. Bluehead Sucker have a distinct cartilaginous ridge on their lower lip that is used to scrape food from hard surfaces. Flannelmouth Sucker do not have the same feature and feed on softer substrates.

Methods

The CPW and the BLM originally planned to use the PHABSIM (Physical Habitat Simulation) software for the instream flow evaluation in Milk Creek. 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. PHABSIM has been widely used in North America to quantify instream flow requirements, and it has been utilized previously by the Colorado Water Conservation Board to quantify instream flow appropriations.

PHABSIM is one component of the Instream Flow Incremental Methodology (IFIM) (Bovee et al. 1998). IFIM was developed in the late 1970s and early 1980s by the US Fish and Wildlife Service Cooperative Instream Flow Group (IFG). IFIM was envisioned as a complete system for instream flow decision making with components for hydraulic habitat, water quality, including water temperature, habitat time series and hydrology time series. PHABSIM is limited to hydraulic habitat simulations with no additional components (Milhous 1999). The comprehensive IFIM software was never completed due to change in direction of management objectives when the IFG became part of the US Geological Survey in early 2000s.

PHABSIM is now legacy software and no longer supported for current Windows operating systems. A newer and currently supported software for hydraulic habitat simulations is System for Environmental Flow Analysis (SEFA) (Payne and Jowett 2011; Jowett et al. 2023). SEFA includes all the hydraulic and habitat simulation functions of PHABSIM and includes additional capabilities to model sediment transport, bioenergetics, water temperature, dissolved oxygen, fish passage and hydrology and habitat time series (Payne and Jowett, 2011).

SEFA uses the same analytical approach to predicting hydraulic parameters as PHABSIM. SEFA uses log-log relationships fitted through survey flows with best fit to calibration measurements to develop the stage-discharge function for hydraulic simulations. Hydraulic habitat is calculated using the same univariate habitat suitability criteria for depth, velocity and substrate as PHABSIM combined with the predicted hydraulic parameters for a range of flows.

SEFA also has the capability to predict fish passage through a study site. The passage criteria can be specified in the analysis and the model calculates the amount of width available for fish passage through the site. SEFA also calculates maximum depth for each cross section and flow simulated. The fish passage analysis and maximum depth prediction provide the data needed for the determination of a minimum flow that provides longitudinal connectivity in the study site and the reach.

Field data collection

Field methods followed the general guidelines of IFIM and SEFA. Stream cross sections were placed in each habitat type at the study site with a metal headpin on the right bank above the high-water mark. The cross sections were placed perpendicular to stream flow with wooden stakes as working pins on both banks. Site elevations were surveyed using differential leveling and referenced to an arbitrary benchmark datum of 100.00 ft. Standard survey techniques were used to establish elevations of all headpins and bed profile elevations relative to the benchmark. Water depth and velocity were measured using a topset wading rod and digital flow meter. This initial data collection in SEFA is referred to as the survey flow. Additional water surface and discharge are measured at additional flows. These additional measurements are referred to as calibration measurements in SEFA.

Hydraulic Modeling

Data for model input and calibration was collected during three separate site visits (Table 1). The initial site visit included placement of cross sections, initial elevation survey, bed profile survey and depth and velocity measurements at all cross sections. The second and third site visits were completed to collect discharge and water surface elevations at two additional flows for model calibration.

Data from the site visits were entered into computer spreadsheets and imported into SEFA software for analysis. SEFA software processing included data entry, hydraulic model calibration, hydraulic model simulations, habitat suitability criteria entry, and hydraulic-habitat model simulations.

Table 1. Site description and measurement dates for Milk Creek instream flow study.

	Distance from confluence with Yampa River (miles)	Site Length (ft)	Number of Cross Sections	Flow 1 - measurement date and discharge	Flow 2 - measurement date and discharge	Flow 3 - measurement date and discharge
Site 1	0.47	639	8	Oct 22, 2023/ 6.26 cfs	April 12, 2024/44.5 cfs	May 29, 2024/127.6 cfs
Site 2	0.94	230	8	Oct 23, 2023/6.06 cfs	April 12, 2024/52.2 cfs	May 29, 2024/127.6 cfs

Data entry was quality checked for errors prior to model simulations. The SEFA software includes a “check” feature to determine that all necessary model data is correctly entered prior to model simulations. SEFA automatically runs all hydraulic simulations when the input file is loaded into the user interface. SEFA also automatically produces calibration details for each simulation. The hydraulic model can be calibrated if necessary to better match the stage-discharge predictions.

Habitat suitability criteria

The criteria for adult Flannelmouth Sucker were updated in early 2024 from a combination of data from radio telemetry studies on the Colorado River near Grand Junction, existing data from a range of rivers and literature review of habitat and population studies (Miller 2024). Additional habitat criteria for Flannelmouth Sucker were incorporated into the final suitability criteria as documented by Miller (2024). The habitat suitability criteria for Flannelmouth Sucker also applies to Bluehead Sucker for this study. Bluehead Sucker feed by scaping on hard substrates and are known to feed in faster riffle habitat with cobble and boulders whereas Flannelmouth Sucker feed on softer substrates in somewhat slower velocities so the habitat response shown for Flannelmouth Sucker may approximate habitat response to flow for Bluehead Sucker but will not fully depict all areas suitable for Bluehead Sucker. The suitability indices used in the hydraulic-habitat modeling is a combination of the data from Flannelmouth Sucker and Bluehead Sucker studies on the Colorado River and literature from the US Fish and Wildlife Service. The suitability indices are listed in Appendix A.

Flannelmouth Sucker and Bluehead Sucker spawn in riffle habitat over gravel and cobble substrate. Spawning habitat use is generally restricted to shallower depths and higher velocity than the broader habitat types used by adults. The spawning habitat suitability criteria for both species were based on a combination of literature review and existing habitat suitability criteria from the US Fish and Wildlife Service. Suitable spawning substrate material was restricted to gravel and cobble substrate types to accurately reflect the use of these sites during spawning (Appendix A).

Results

SEFA modeling steps were identical for Milk Creek Site 1 and Site 2. Hydraulic models were completed for flows from 5 cubic feet per second (cfs) to 300 cfs at each site for model calibration. Habitat suitability criteria were selected for the hydraulic-habitat simulations for each site after checking model calibration results. No hydraulic calibration was needed for either site. Hydraulic-habitat simulations were completed for flows from 5 cfs to 100 cfs at each site. A fish passage analysis was completed after the hydraulic-habitat simulations to evaluate longitudinal connectivity at base flows.

Hydraulic Model Results

The stage-discharge relationships for both sites were similar with the R-square for the rating curves ranging from 0.989 to 1.00 for Site 1(Table 2) and ranging from 0.980 to 0.999 for Site 2 (Table 3). SEFA generates graphs of the rating curves for each cross section that also can be used to evaluate model calibration. The high R-square values result in very closing fitting predictions based on the measured flows at each site. Examples of the fit are shown for Site 1 (**Error! Reference source not found.**) and Site 2 (**Error! Reference source not found.**). No hydraulic model calibration was needed at either site prior to simulation of hydraulic-habitat.

Table 2. Site 1 ratings curves from SEFA model.

Cross Section	Selected rating type	Exponent	Constant	Stage of ZeroFlow	R^2
XSEC1	SZF rating	3.790	23.650	94.130	1.000
XSEC2	SZF rating	4.217	5.869	94.130	0.992
XSEC3	SZF rating	3.873	6.618	94.250	0.992
XSEC4	SZF rating	3.210	24.394	95.510	0.990
XSEC5	SZF rating	4.401	3.574	96.530	0.989
XSEC6	SZF rating	4.351	3.596	96.530	0.992
XSEC7	SZF rating	3.410	14.279	97.000	0.993
XSEC8	SZF rating	3.643	4.783	97.000	0.997

Table 3. Site 2 ratings curves from SEFA model.

Cross Section	Selected rating type	Exponent	Constant	Stage of Zero Flow	R^2
XSEC1	SZF rating	3.195	18.938	94.580	0.999
XSEC2	SZF rating	3.335	6.060	94.620	0.980
XSEC3	SZF rating	3.172	6.060	94.620	0.997
XSEC4	SZF rating	3.333	5.151	94.620	0.991
XSEC5	SZF rating	2.606	45.847	95.750	0.986
XSEC6	SZF rating	3.227	20.068	95.750	0.991
XSEC7	SZF rating	3.104	18.337	95.750	0.989
XSEC8	SZF rating	3.300	10.773	95.750	0.982

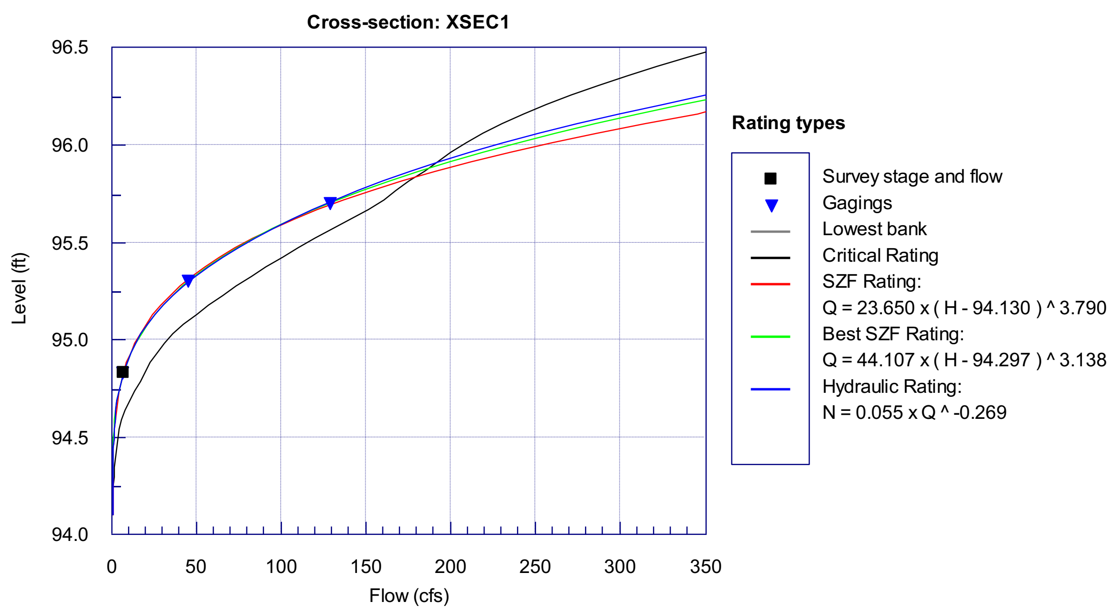

Figure 2. Site 1- example hydraulic calibration and predicted rating curve.

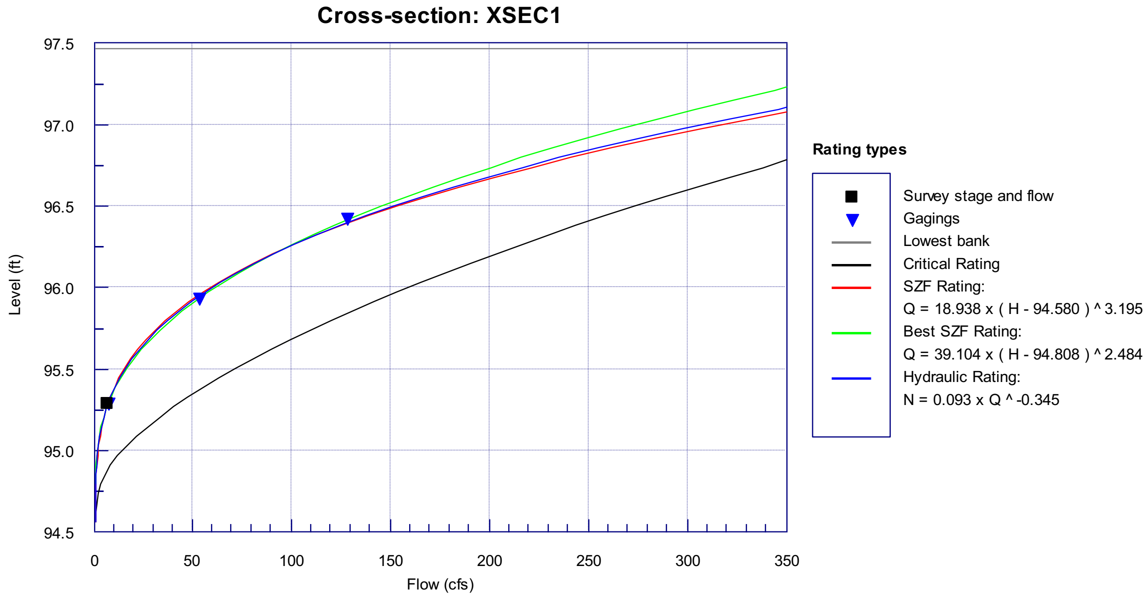

Figure 3. Site 2 - example hydraulic calibration and predicted rating curve.

Milk Creek Hydrology

The Milk Creek flow regime is typical of snowmelt – runoff hydrology in Colorado. No long-term streamflow gage data is available in the proposed instream reach. CWCB installed a temporary gage in 2017 in an effort to better understand the hydrology in the reach. Peak streamflows occur in May and June, base flows occur from August through February, March-April and July flows are the ascending and descending limb of the hydrograph, respectively (Figure 4). Stream flow in the study reach is affected by upstream diversions for irrigation and municipal/industrial uses. Peak flows can be over 400 cfs in high flow years. Mean peak flow from preliminary data is calculated at approximately 115 cfs **Error! Reference source not found.**.

CWCB developed preliminary mean-monthly hydrology estimates based on the available gage data collected as of August 2024. These estimates include data from low flow years such as 2018 and 2020 as well as high flow years like 2019. The average monthly data show the snowmelt runoff period is from April through June. The lowest base flows occur in late summer into fall with mean monthly flows slightly lower than 5 cfs (Table 4).

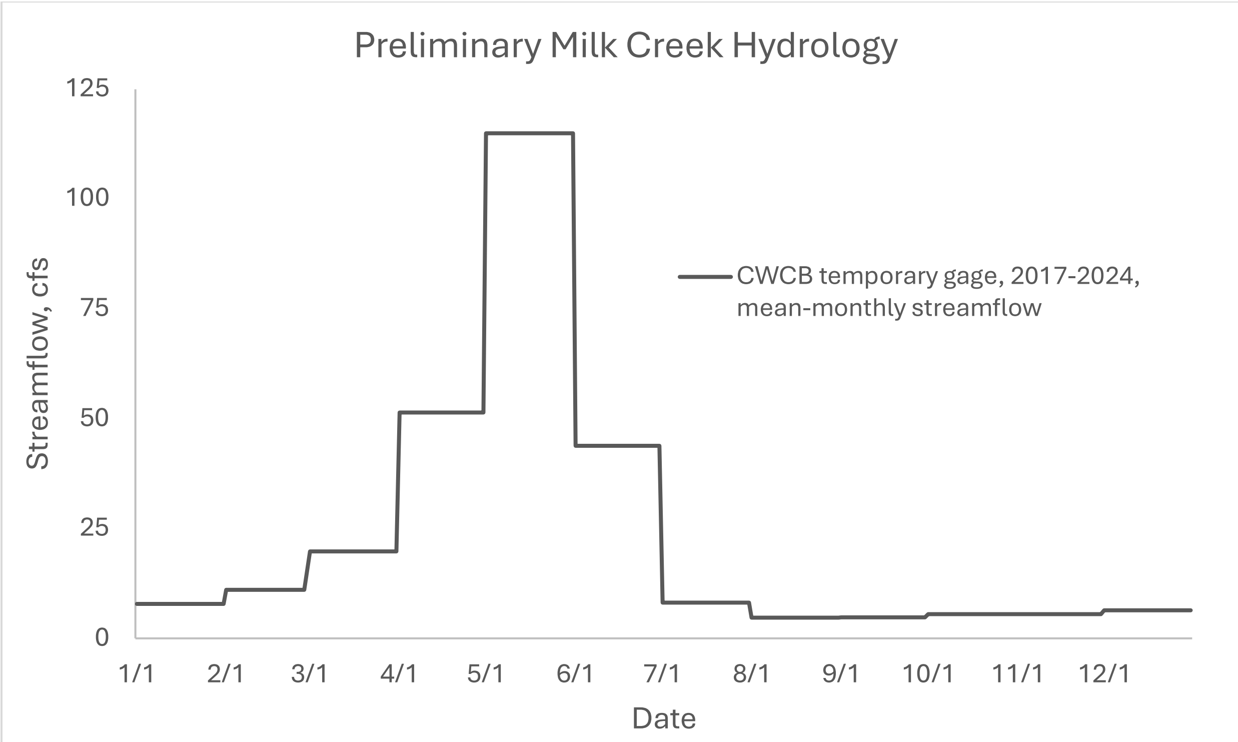

Figure 4. Milk Creek discharge from CWCB temporary gage, 2017 – 2024.

Table 4. Milk Creek mean monthly discharge for the period of record 2017 – 2024.

Month	Mean Monthly Value (cfs)
Jan	7.8
Feb	11.0
Mar	19.7
Apr	51.4
May	114.9
Jun	43.8
Jul	8.0
Aug	4.7
Sep	4.8
Oct	5.4
Nov	5.5
Dec	6.3

Habitat Model Results

SEFA produces a habitat index calculation of "Average Weighted Suitability" (AWS) to describe the hydraulic-habitat relationship to discharge. This calculation is similar to the PHABSIM habitat versus discharge function of "Weighted Usable Area". The results of the hydraulic-habitat function are expressed as area (ft^2) per linear distance (ft). The AWS is the Combined Suitability Index (CSI) for depth, velocity and substrate for each measurement point weighted by the area the point represents (Payne and Jowett 2011).

The maximum AWS for adult sucker habitat occurs at a flow of 40 cfs at both sites (Figure 5, Figure 6). The habitat index rapidly decreases for adult habitat as flow drop below 40 cfs. A flow of 10 cfs results in approximately 60% of the maximum habitat index. The habitat index has a less rapid decline for flows greater than 40 cfs. A flow of 100 cfs still has approximately 80% of the maximum habitat index.

The maximum AWS for spawning habitat occurs from 30 cfs to 40 cfs for both sites. There is very little difference between the spawning habitat index value at 30 cfs and 40 cfs (Figure 5, Figure 6). The shape of the AWS versus discharge function for spawning habitat is similar to the adult habitat discharge function with a steep decline in habitat as flows drop below 30 cfs. A flow of 10 cfs produces approximately 65% of the maximum potential habitat at Site 1 and approximately 58% of the maximum habitat potential at Site 2. The spawning habitat index at 100 cfs is slightly higher than 60% of the maximum habitat index at both sites.

The habitat time series shows the monthly change in average weighted suitability as a function of the average monthly flow. Adult and spawning habitat is highest at Site 1 and Site 2 during April though June when flows are greater than 40 cfs (Figure 7 ,Figure 8).

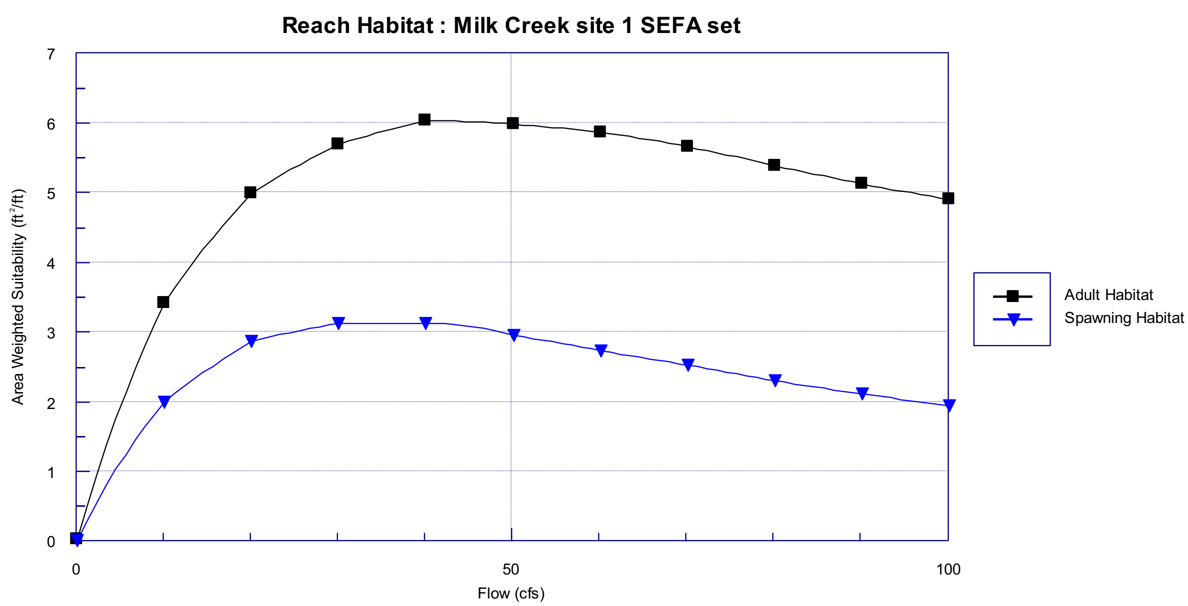

Figure 5. Milk Creek Site 1 predicted average weighted suitability as a function of discharge for adult and spawning Flannelmouth and Bluehead Suckers.

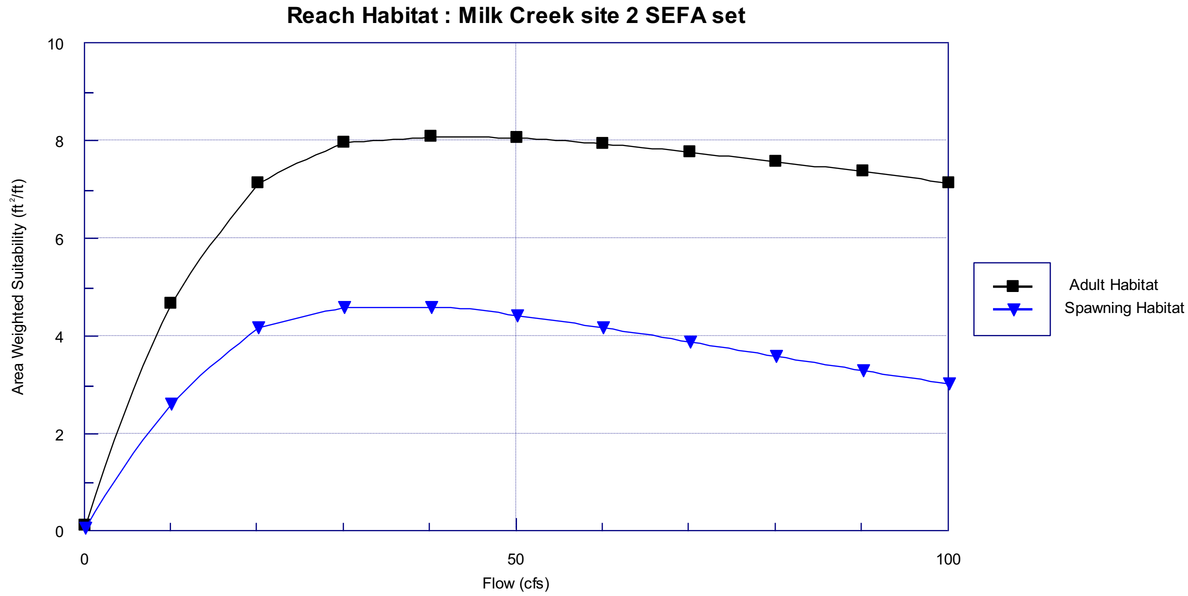

Figure 6. Milk Creek Site 2 predicted average weighted suitability as a function of discharge for adult and spawning Flannelmouth and Bluehead Suckers.

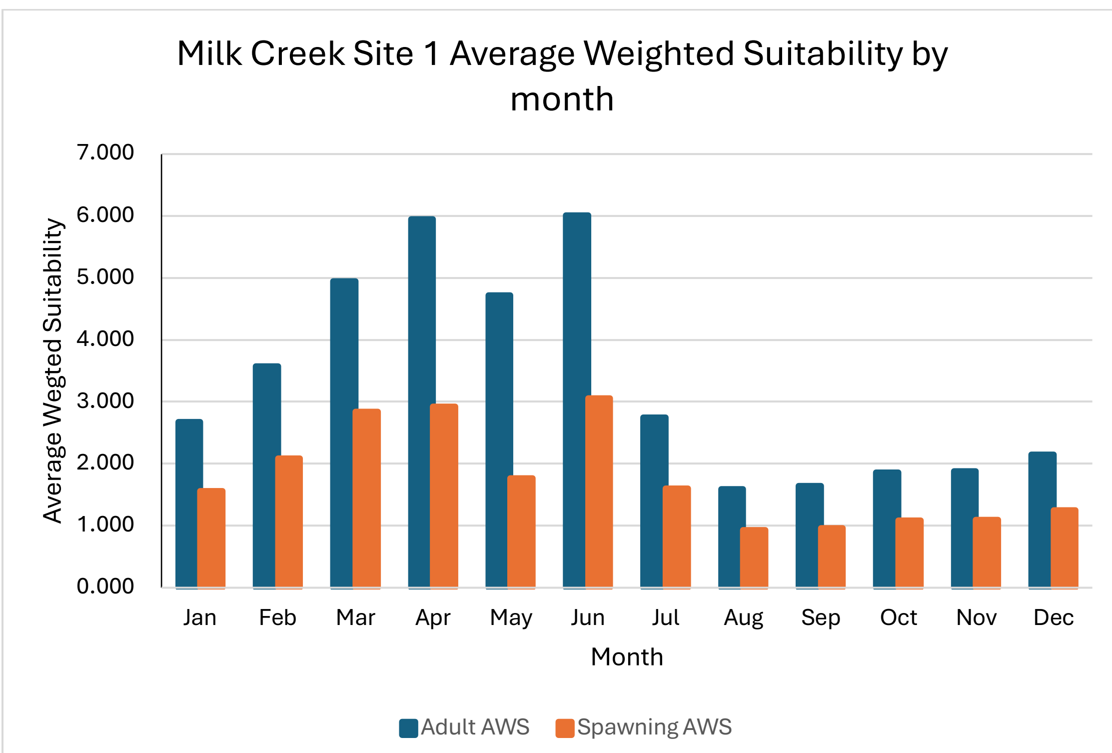

Figure 7. Milk Creek Site 1 average weighted suitability by month for adult and spawning Flannelmouth and Bluehead Suckers.

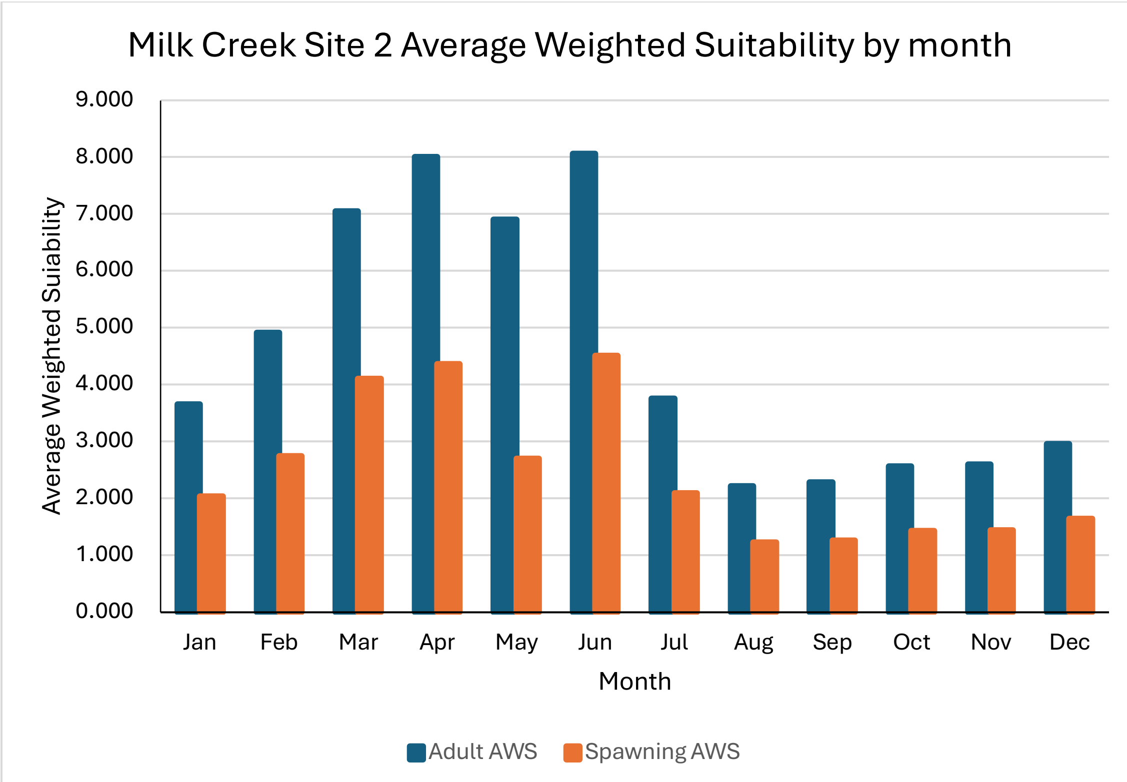

Figure 8. Milk Creek Site 2 average weighted suitability by month for adult and spawning Flannelmouth and Bluehead Suckers.

Longitudinal connectivity is important in riverine systems to allow migration and localized movement required by fish and other aquatic biota (Annear et al. 2004). Analysis of fish passage is one means to assess connectivity and evaluate the flows needed to allow fish migration. Flannelmouth Sucker and Bluehead Sucker migrate from larger rivers into smaller tributary streams for spawning. A passage criterion of 0.6 foot (7 inches) of depth was chosen based on professional judgement to evaluate fish passage for the native suckers. This depth is approximately double the body depth of adult Flannelmouth Suckers (the larger of the two species), which should allow passage. The SEFA fish passage/connectivity analysis for Milk Creek showed a flow of 8 cfs there is a continuous pathway for fish passage through all cross sections that is at least 2 feet in width and at least 0.6 feet in depth at Milk Creek Site 1 (Figure 9) and Milk Creek Site 2 (Figure 10). The maximum depth analysis showed that a maximum depth of 0.6 feet in depth was present at some point in all cross sections at an average flow 4.6 cfs except for one of the seven shallowest cross sections. Fish movement across these shallow stream areas may be possible at flows as low as 4.6 cfs but movement may be slowed or temporarily impeded. Downstream movement may be less impeded for out migrating fish since the movement is in the same direction as the downstream velocity.

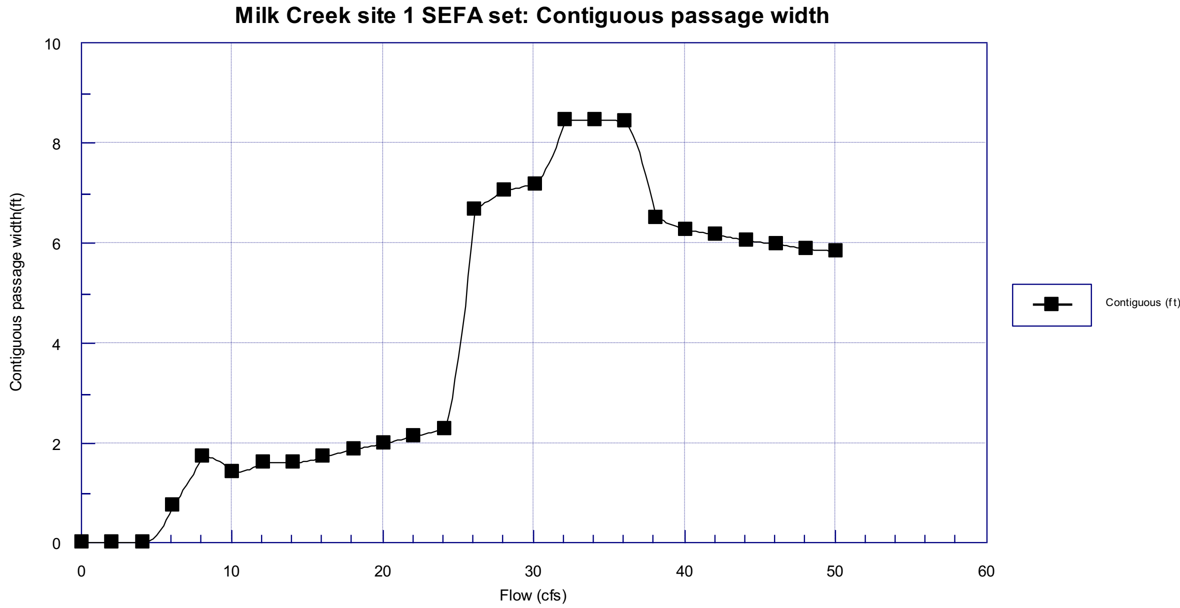

Figure 9. Milk Creek Site 1 predicted contiguous passage width as a function of discharge.

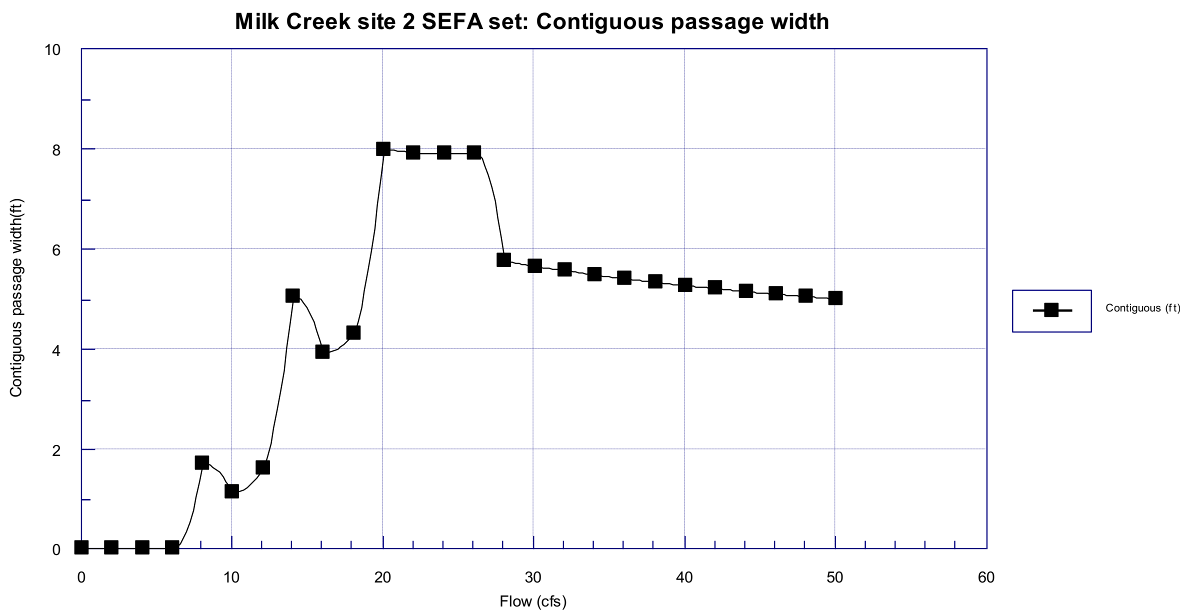

Figure 10. Milk Creek Site 2 predicted contiguous passage width as a function of discharge.

Discussion/Conclusion

The Milk Creek instream flow study used current state of the science methods to quantify fish habitat in the study reach. The study used field data from two representative study sites and SEFA software to quantify the relationship of habitat as a function of stream flow. The field methods included multiple measurements of stream flow and water surface elevations for model calibration. The multiple measurements include flows for low base flow (less than 10 cfs), mid-range flows of 40-50 cfs and a moderately high flow of 126 cfs. The range of flow measurements provided data for a well calibrated hydraulic model.

The study sites and cross sections at both study sites included representation of all habitat types in the study reach. Each study site had eight cross sections which included replicate measurements of habitat types (riffle, pool, run) at each site. Each study site included habitat types for adult and spawning life stages of the two native suckers.

Stream flow of 30-40 cfs produces the maximum habitat for both adult and spawning life stages. Habitat availability declines at flow lower and higher than the maximum. Flannelmouth Sucker and Bluehead Sucker spawn from spring to early summer, which coincides with the snowmelt-runoff peak flow in the stream. Protecting a minimum flow during snow melt runoff (April-June) of 40 cfs would provide unimpeded fish passage for fish migrating into Milk Creek and the most spawning habitat. The hydrology data demonstrate that a flow of 40 cfs is likely available in most years.

Adult Flannelmouth Sucker and Bluehead Sucker migrate into tributary streams prior to the spawning period. Adequate streamflow is needed for longitudinal connectivity to allow migrating fish to move upstream. A minimum streamflow of 8 cfs is the flow at which fish passage through the study reach is possible. Flows lower than 8 cfs would likely make upstream migration difficult or unlikely. Passage increases as flow increase above 8 cfs.

Summer, fall and winter baseflows are needed to support resident native fish and the lower trophic levels that provide food resources for fish species. A base flow of 8 cfs provides the minimum flow at which passage is possible for resident and migratory fish, provides approximately 60% of the maximum habitat available for adult suckers, and provides approximately 60% of the maximum wetted perimeter at each site.

Appropriate flows for the ascending and descending limb of the hydrograph would allow more unimpeded movement for migration and for resident fish moving to spawning locations. A streamflow that is intermediate between the recommended base flow and peak flow would be more protective of the species than an abrupt change from baseflow to peak. An intermediate flow for the ascending and descending limb of the hydrograph based on water availability would be protective.

Summary of recommended instream flows for protection of native sucker in Milk Creek.

- Baseflow- August – March: 8 cfs
- Ascending and Descending limb – Based on water availability
- Peak flow- April-June: 40 cfs

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Author's Biography

Dr. William J. Miller has over 44 years experience in fisheries, instream flow, and aquatic ecology studies. He has worked extensively throughout the western U.S. and is a recognized expert in the areas of instream flow, water temperature modeling and habitat assessments. Dr. Miller's experience includes research and evaluations for several threatened, endangered, and candidate aquatic species in the Colorado River, Platte River, Columbia River, and Missouri River basins. He has completed instream flow studies outside of the contiguous 48 states in Alaska and Puerto Rico. He has extensive experience in designing and conducting studies using the Instream Flow Incremental Methodology (IFIM), instream water temperature modeling and developing and implementing ecological models for aquatic systems. Dr. Miller is a former member of the USFWS Instream Flow Group. He is co-author on the Stream Network Temperature Model, Instream Flow Information Paper 16. Dr. Miller has conducted seminars and training on instream flow techniques for federal, state, tribal and private entities.

Dr. Miller's experience includes designing and directing basinwide instream flow evaluations. He has completed instream flow evaluations for US Forest Service, US Fish and Wildlife Service, Bonneville Power Administration, U.S. Army Corps of Engineers, the U.S. Department of Justice and the Bureau of Land Management. Dr. Miller developed a GIS based methodology for determining flow/habitat relationships for aquatic species using 2 dimensional hydraulic modeling and habitat evaluations. Dr. Miller has presented his research at national conferences in the US and international conferences in Japan and New Zealand. Dr. Miller has testified as an instream flow expert in water court hearings in Colorado, Nebraska, California and Arizona.

Appendix A – Habitat Suitability Criteria

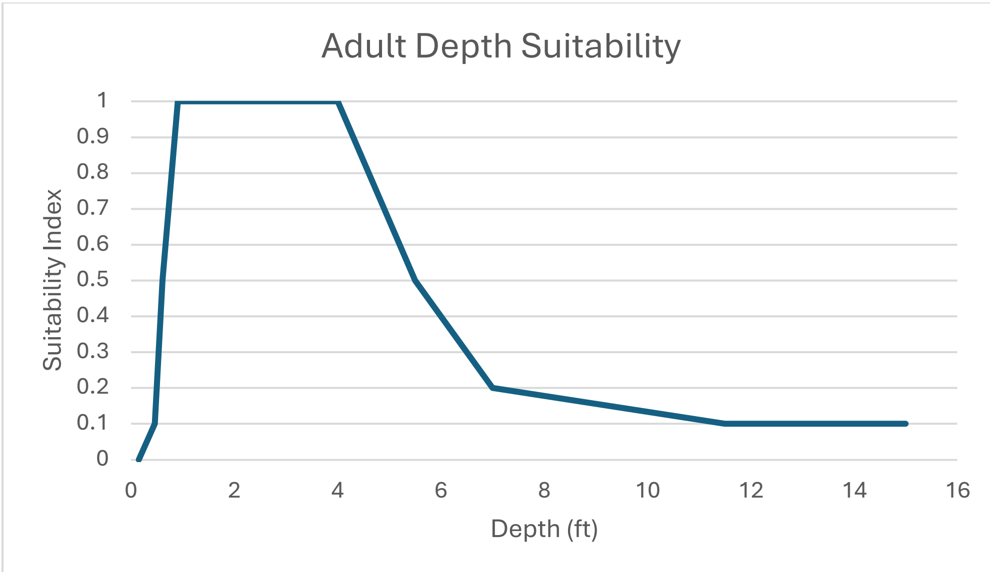

Figure A-1. Adult Depth Suitability Index for Flannelmouth Sucker and Bluehead Sucker. Data sources were values from Colorado River depth observation SI and USFWS published SI.

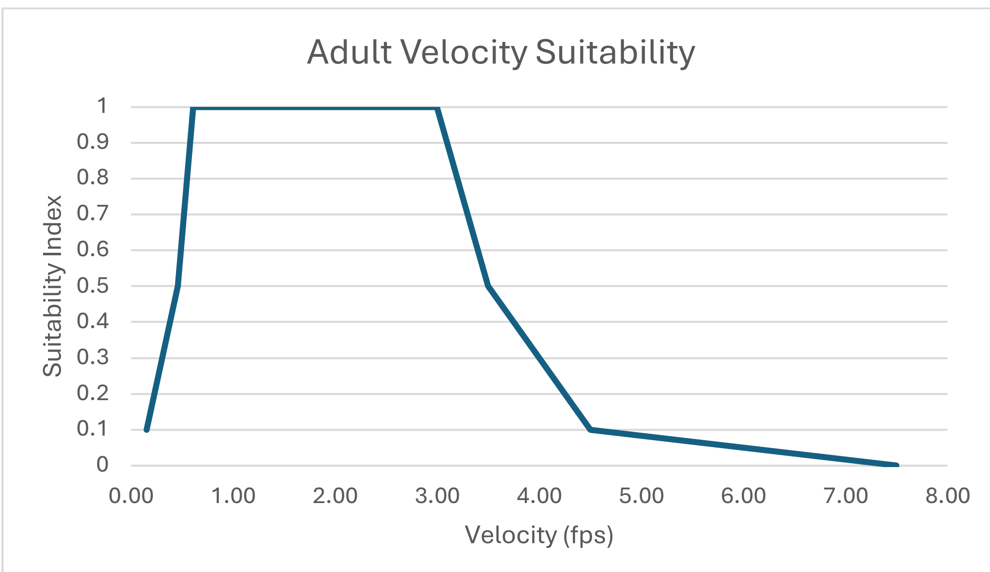

Figure A-2. Adult Velocity Suitability Index for Flannelmouth Sucker and Bluehead Sucker. Data sources were values from Colorado River velocity observation SI and USFWS published SI.

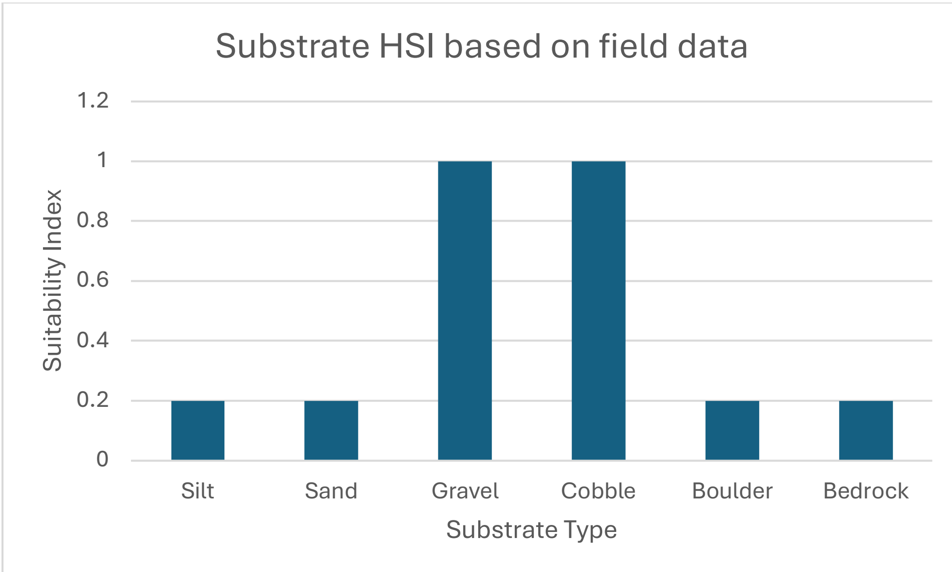

Figure A-3. Adult Flannelmouth Sucker and Bluehead Sucker substrate suitability index based on field data collection.

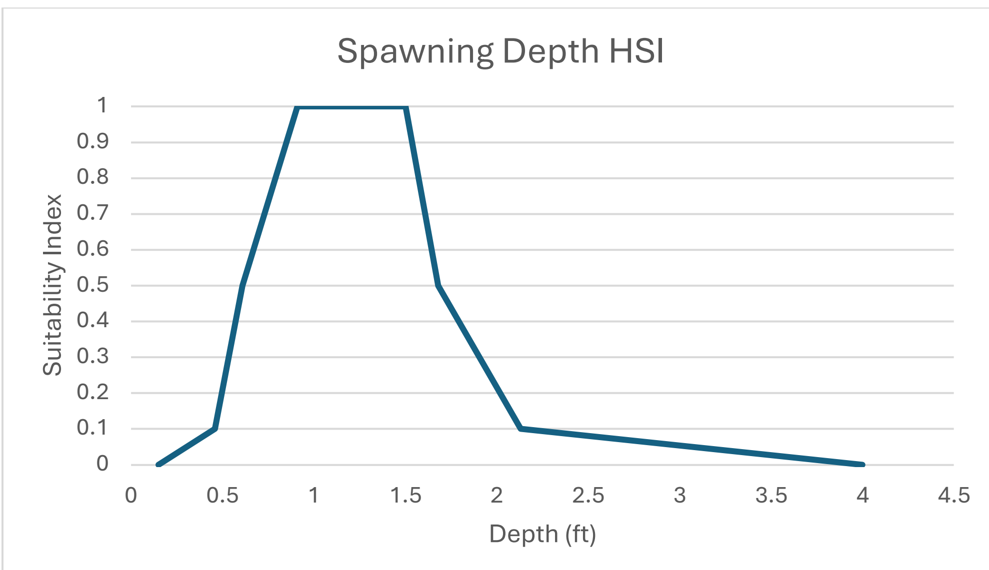

Figure A-4. Flannelmouth Sucker and Bluehead Sucker spawning depth suitability index based on life history traits and adult habitat use.

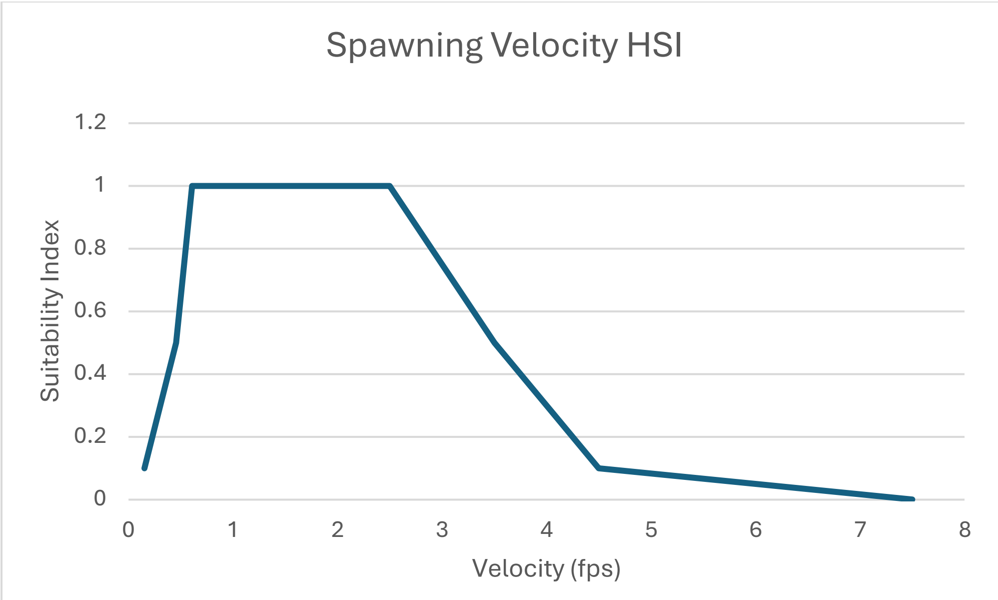

Figure A-5. Flannelmouth Sucker and Bluehead Sucker spawning velocity suitability index based on life history traits and adult habitat use.

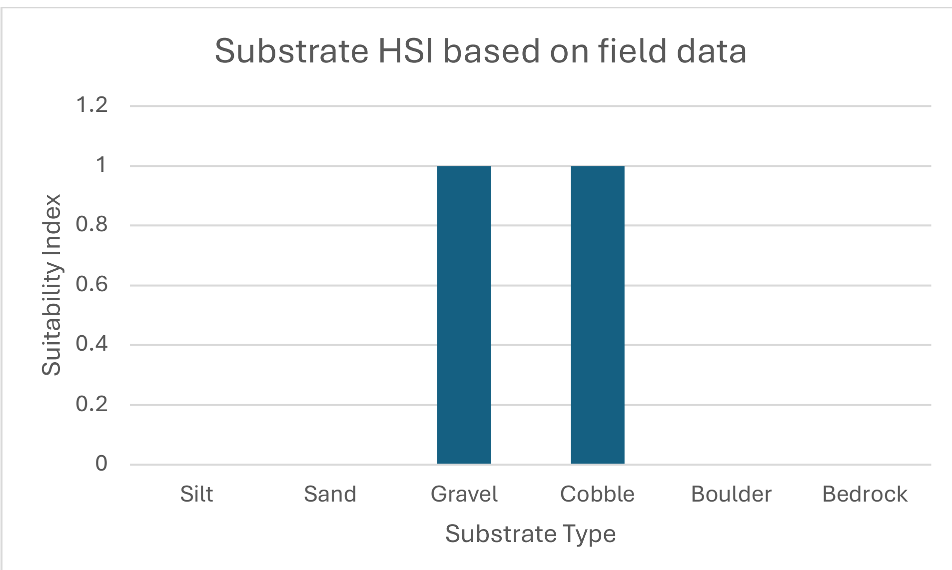

Figure A-6. Flannelmouth Sucker and Bluehead Sucker spawning substrate suitability index based on life history traits and adult habitat use.

Proposed Habitat Suitability Criteria for Flannelmouth Sucker and Bluehead Sucker for use in Milk Creek Instream Flow Study

Submitted to:

Colorado Water Conservation Board
Denver, Colorado

Submitted By:

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January 26, 2024

Introduction

This report describes the process used to select and recommend the habitat suitability criteria for the species of interest in the Milk Creek Instream Flow study. The species of interest for this study are Flannelmouth Sucker (*Catostomas latipinnis*) and Bluehead Sucker (*Catostomas discobolus*). One dimensional hydraulic models such as Physical Habitat Simulation System (PHABSIM) and System for Environmental Flow Analysis (SEFA) use univariate habitat suitability criteria in the computer modeling. These habitat suitability criteria are expressed as a suitability index value (SI) for each physical flow component of water depth, water velocity, and channel index (substrate or cover). The terms habitat suitability criteria, suitability curves, or suitability indices are used interchangeably with the same meaning. The suitability criteria in this report were developed using available field data, literature review and professional judgement following guidelines in Bovee (1986).

Habitat Suitability Curves

Species habitat suitability criteria are required for the one-dimensional habitat analysis. Habitat suitability criteria that accurately reflect the habitat requirements of the species of interest are essential to conducting meaningful and defensible habitat analyses. The curves proposed for this study fit that criterion. The preferred approach is to collect new data to develop site-specific criteria for each species and life stage of interest (Bovee 1986), however, this is not always practical due to site specific and logistic factors. Habitat suitability indices for use in instream flow studies require point location data for water depths, velocities, substrates, and cover types used by each life stage of the target species. The collection of new site-specific or stream specific data is not always feasible due to lack of species presence and time constraints of the study. An alternative approach which follows IFIM guidelines is the use existing curves, data from other studies and literature to develop suitability criteria for species of interest. This study used the alternative approach.

The majority of the existing habitat suitability criteria for use in instream flow studies are for game species. There are limited existing habitat suitability criteria for the two non-game native species of interest for this study, Flannelmouth Sucker and Bluehead Sucker. There is one habitat suitability curve set for Flannelmouth Sucker in the older “FISHFIL” data from USFWS PHABSIM archives. The FISHFIL suitability curve library was a compilation of multiple species and life stages developed in the late 1970s and early 1980s by the USFWS. The source of the data used for the curve set is not stated and based on the data range in the graphs of the Flannelmouth Sucker SI curve set it appears to be from a smaller stream.

Habitat specific data for adult Flannelmouth Sucker and adult Bluehead Sucker were collected during studies on the Colorado River in the early 2000s (Beyers et al. 2001, Rees and Miller 2001). The study sites for those two investigations were on the Colorado River near Grand Junction, Colorado where habitat features including depths and velocities exceed those in Milk Creek. A summary of depth and velocity use data for native species, including Flannelmouth Sucker and Bluehead Sucker was completed in 2023 (Lewis and Kanno 2023). The summary synthesized the findings from multiple publications and reports for studies on range of streams and rivers and provided the range and mean depth and velocities from those studies, however, no individual data sets were included. Miller et al. (1995) collected data from the La Plata River on habitat characteristics for depth by habitat with concurrent fish captures. Bower et al. (2008) collected fish capture data by habitat, which included water depths of the habitats. Underwood et al. (2014) tested swimming capabilities of Bluehead Suckers and Flannelmouth Suckers at a range of velocities. Stewart and Anderson (2009) completed fish population estimates in conjunction with two-dimensional hydraulic modeling to predict biomass based on stream hydraulic parameters of depth and velocity. All of the above reports and data sets were reviewed and synthesized into the habitat suitability criteria proposed for the Milk Creek instream flow study.

Depth Habitat Use Criteria

Depth habitat use is similar for the larger summary data set and the site specific data as shown in the graph comparing Lewis and Kanno (2023) summary and the site specific Colorado River data (Figure 1). Additional studies by Stewart and Anderson (2009) and Yao and Chen (2018) also report habitat use for adult Flannelmouth Sucker.

Flannelmouth Sucker and Bluehead Sucker general show use of similar water depths. Maximum water depths were reported approximately 6 feet deep and deeper. Byers et al. (2001) reported use of depths greater than 10 feet. Minimum water depths were reported as approximately 0.5 feet. Mean water depths ranged from approximately 2.5 to 3.5 feet deep. One distinct difference is the minimum depth and mean depth reported for Bluehead Sucker in the Colorado River data set. These differences are likely due to the very low number of observations (11) for Bluehead Sucker compared to the higher number of observations (134) for Flannelmouth Sucker. Histogram of depth data shows that the Bluehead Sucker data is nested within the Flannelmouth Sucker data set, which indicates the use of similar depths for these species (Figure 2).

Physical characteristics of La Plata River habitats were measures during July, 1994 concurrent with fish captures. The data were collected for use in the native fish study for the Animas-La Plata EIS (Miller et al. 1995). Reaches 2-4 are located from the Colorado-New Mexico state line upstream to Cherry Creek, approximately 15 miles. Average depths for riffles and glides range from 0.6 feet to approximately 1.2 feet (Table 1). Average pool depths range from 1.4 feet to 1.9 feet. Maximum pool depths were approximately 4.5 feet. The fish collections show that majority of the captures for Bluehead and Flannelmouth suckers were in riffles and glides followed by pools (Table 2).

Depth SI was constructed from the Colorado River data using the non-parametric tolerance method as outlined in Bovee (1986). The SI values range from 0.0 (unusable) to 1.0 (highest used). The SI is a two tailed index with the peak values occurring between 3 feet and 4 feet deep (Figure 3). The FISHFIL SI for adult Flannelmouth

Sucker shows a minimum usable depth of approximately 0.5 feet and peak SI values for depths that range from approximately 1 foot to 1.3 feet deep (Figure 4). The La Plata River data reported by Miller et al. (1995) confirms the use of this range of depth values for the FISHFIL curve

These two individual depth SI curves include use for both shallow and deeper stream conditions. The data from Lewis and Kanno (2023) includes data for depths over a wide range of stream conditions from large rivers to smaller streams. Data for pool depths by Bower et al. (2008) included depths of 6 feet concurrent with captures of native suckers. Depth data from Beyers et al. (2001) show habitat use at depths greater than 10 feet. Stewart and Anderson (2009) report depths greater than 6 feet as usable habitat. It seems appropriate that a Suitability Index should include the full range of observed conditions. As such the recommended SI for depth is a combined function that uses the SI values from the USFWS criteria for the shallower depths and the Colorado River site specific criteria for the deeper conditions (Figure 5) as supported by the additional field data from Bower et al (2008) and Miller et al. (1995).

Velocity Habitat Use Criteria

Flannelmouth Sucker and Bluehead Sucker have more variability in velocity use than depth use (Figure 6). Lewis and Kanno (2023) report the velocity use from a minimum of near 0.4 fps to a maximum of just over 3.0 fps. Underwood et al. (2014) reported maximum sustained swimming speeds for Bluehead Sucker and Flannelmouth Sucker adults near 3.5 feet per second. Colorado River velocity observations for these two species ranged from -0.1 fps to 4.5 fps. Stewart and Anderson (2009) reported use of velocities between 0.3 fps and 5.8 fps. Peak habitat use was reported between 1.5 fps and 4.5 fps. Average velocity use was less variable when comparing the summarized data of Lewis and Kanno with the site-specific data from the Colorado River. Again, the largest difference was the site specific Bluehead Sucker data from the Colorado River and likely due to the small observation data set.

The site-specific velocity data for Flannelmouth Sucker and Bluehead Sucker shows that habitat use for Bluehead Sucker is nested within the Flannelmouth Sucker data (Figure 7). Since the data for Bluehead Sucker are within the bounds of the Flannelmouth sucker data, it seems reasonable to combine the data sets. Further, it also is reasonable to construct the velocity suitability index from the entire data set and apply the resulting SI to both species.

The velocity suitability index for the site-specific Colorado River data has a minimum SI value at 0.0 fps. The peak SI values occur between 2.0 fps and 2.5 fps (Figure 8). The FISHFIL velocity SI values are shifted to slower velocities than the Colorado River data (Figure 9). This shift is likely due to collection of the data from smaller streams rather than large rivers, however, there is no documentation to confirm this hypothesis.

The use of the broader range for velocity conditions is shown in the data summary from Lewis and Kanno (2023) and the site-specific Colorado River data. To use the full range of velocity conditions a combined SI curve was constructed by merging the two SI curves from the USFWS and the Colorado River (Figure 10).

Channel Index Habitat Use Criteria

The channel index criteria can represent either stream substrate or cover. In this application the channel index represents substrate. There is less data for stream substrate use than available for depth and velocity. Lewis and Kanno (2023) did not summarize stream substrate use in a quantitative format. They did include statements in the report narrative that suggests most used substrate is “rocky” with some mention of other substrate types. This implies that anything from clean gravel to cobble is used by these two species. The most used substrate for the Colorado River data set was cobble with fewer observations in other substrate types (Figure 11). The USFWS channel index criteria shows all substrate as suitable (Figure 12). Bottcher (2009) reports gravel and small cobble as the most used substrate with lower use of other substrate types (Figure 13). The recommended substrate index is to have maximum index value for gravel and cobble with lower suitability of other substrate types (Figure 14).

Recommended Adult Suitability Indices

There are limited number of studies that document habitat use for either Flannelmouth Sucker or Bluehead Sucker. There is more quantitative data for Flannelmouth Sucker but it is limited to the adult life stage and from a large river. The data that is available for Bluehead Sucker falls within the boundaries of the habitat use by Flannelmouth Sucker. It seems reasonable to combine the data sets and use a single Suitability Index Criteria for both species. Based on the data and reports available, the SI curves recommended for the Milk Creek Instream Flow study are the combined SI curve for depth (Figure 5), the combined SI curve for velocity (Figure 10), and the field data observations SI for substrate (Figure 14). The data points for these SI curves are listed in Table 1.

Spawning Suitability Indices

There are no studies that directly measured habitat use during spawning for either species. Several studies report the use of smaller tributaries in the Colorado River Basin during spawning (Hooley-Underwood et al. 2019; Cathcart et al. 2015). Life history studies of these two species report spawning in riffle habitat over clean gravel or cobble substrate during the ascending limb and peak runoff, generally in late March through May. The use of this type of habitat is confirmed by population abundance sampling (Ryden 2005).

The recommended spawning SI curves are modifications to the adult SI curves based on literature review and knowledge of habitat use during spawning. Depth SI curve is a modification to the adult depth criteria that has peak suitability between 1 foot and 1.5 foot of water depth (Figure 15). This depth range provides adequate depth for fish movement in riffle habitat during spawning activities.

The velocity SI curve for spawning also is a modification of the adult velocity curve. The peak SI values are in the velocity range of 1 fps to 2.5 fps (Figure 16). These values are typical of velocities found in riffle habitat during moderate flows associated with the seasonality of spawning.

Flannelmouth sucker and Bluehead Suckers are broadcast spawners. The demersal eggs sink to the stream bottom and into the clean stream substrate for incubation and emergence. This life history trait requires a clean substrate with adequate interstitial space to allow the eggs fall into the substrate (Rees et al. 2005; Ptacek et al. 2005). The proposed spawning substrate SI curve reflects this requirement by limiting the suitable substrate to gravel and cobble (Figure 17).

The recommended spawning SI curve values are listed in tabular form for use in the instream flow study (Table 4).

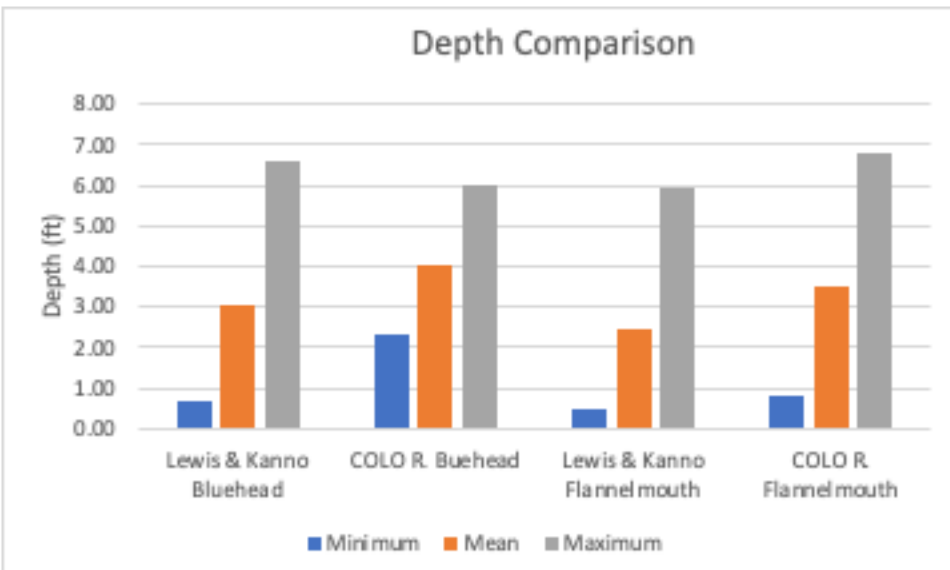

Figure 1. Comparison of depths used by Flannelmouth Sucker and Bluehead Sucker.

Table 1. Habitat measurements for La Plata River, July 1994

LA PLATA - REACH 2 summer 94

	POOL	RIFFLE	GLIDE	REACH TOTAL		POOL	RIFFLE	GLIDE	REACH TOTAL
TOTAL LENGTH OF HABITAT (ft.)	754.0	1227.0	1277.0	3258.0	TOTAL AREA OF HABITAT (sq. f	14196.0	23427.0	19725.0	57348.0
AVERAGE WIDTH OF HABITAT (	20.6	18.9	15.6	18.4	% OF TOTAL NUM. OF HABITATS	30.8	33.3	35.9	100.0
AVERAGE RESIDUAL DEPTH (ft	2.4	0.0	0.0	2.4	HABITAT TYPE AS A % OF TOTAL AREA	24.8	40.9	34.4	100.0
AVERAGE DEPTH (ft.)	1.9	0.6	1.0	1.9					

LA PLATA - REACH 3 summer 94

	POOL	RIFFLE	GLIDE	REACH TOTAL		POOL	RIFFLE	GLIDE	REACH TOTAL
TOTAL LENGTH OF HABITAT (ft.)	2663.00	2522.00	2643.00	7828.00	TOTAL AREA OF HABITAT (sq. ft.)	38912.0	36519.0	34041.0	109472.0
AVERAGE WIDTH OF HABITAT (ft.)	14.12	14.04	13.21	13.79	% OF TOTAL NUM. OF HABITATS	37.6	36.7	25.7	100.0
AVERAGE RESIDUAL DEPTH (ft.)	3.30	0.00	0.00	3.30	HABITAT TYPE AS A % OF TOTAL AREA	35.5	33.4	31.1	100.0
AVERAGE DEPTH (ft.)	1.88	0.57	1.17	1.88					

LA PLATA - REACH 4 summer 94

	POOL	RIFFLE	GLIDE	REACH TOTAL		POOL	RIFFLE	GLIDE	REACH TOTAL
TOTAL LENGTH OF HABITAT (ft.)	245.00	524.00	485.00	1254.00	TOTAL AREA OF HABITAT (sq. ft.)	4421.0	9349.0	7526.0	21296.0
AVERAGE WIDTH OF HABITAT (ft.)	17.75	17.00	14.80	16.52	% OF TOTAL NUM. OF HABITATS	28.6	35.7	35.7	100.0
AVERAGE RESIDUAL DEPTH (ft.)	1.80	0.00	0.00	1.80	HABITAT TYPE AS A % OF TOTAL AREA	20.8	43.9	35.3	100.0
AVERAGE DEPTH (ft.)	1.40	0.78	1.06	1.40					

Table 2. Fish capture by habitat type, La Plata River July 1994.

Number of fish captured	Habitat type				
Species	**Glide**	**Glide/Riffle**	**Pool**	**Riffle**	**Grand Total**
Bluehead Sucker	686	0	568	219	1473
Flannelmouth Sucker	1685	4	1443	226	3358
Mottled Sculpin	28	0	12	8	48
Roundtail Chub	26	1	114	0	141
Speckled Dace	3869	62	1902	5873	11706
Grand Total	6294	67	4039	6326	16726

Percent capture by habitat	Habitat type				
Species	**Glide**	**Glide/Riffle**	**Pool**	**Riffle**	**Grand Total**
Bluehead Sucker	46.6	0.0	38.6	14.9	100.0
Flannelmouth Sucker	50.2	0.1	43.0	6.7	100.0
Mottled Sculpin	58.3	0.0	25.0	16.7	100.0
Roundtail Chub	18.4	0.7	80.9	0.0	100.0
Speckled Dace	33.1	0.5	16.2	50.2	100.0
Grand Total	37.6	0.4	24.1	37.8	100.0

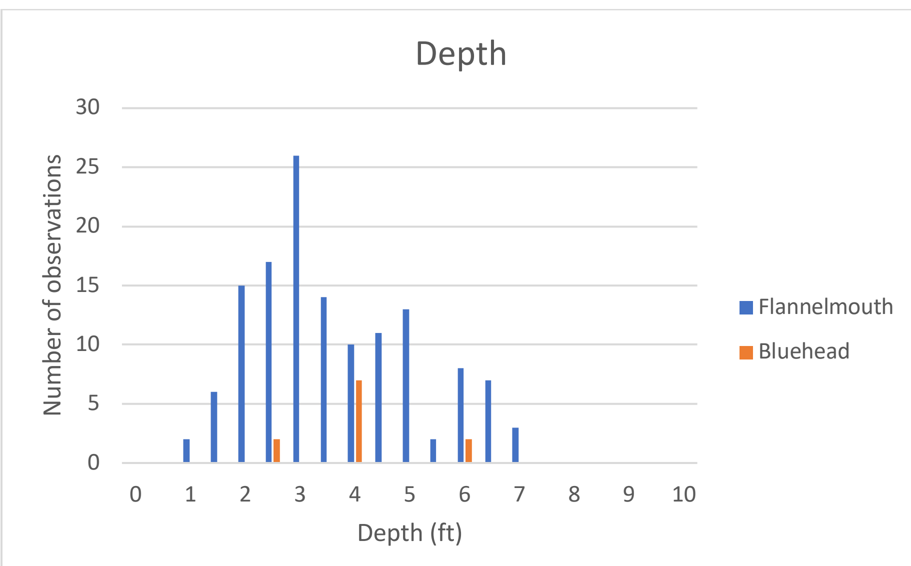

Figure 2. Colorado River depth data for Flannelmouth Sucker and Bluehead Sucker. Source: Beyers et al. 2001 and Rees and Miller 2001.

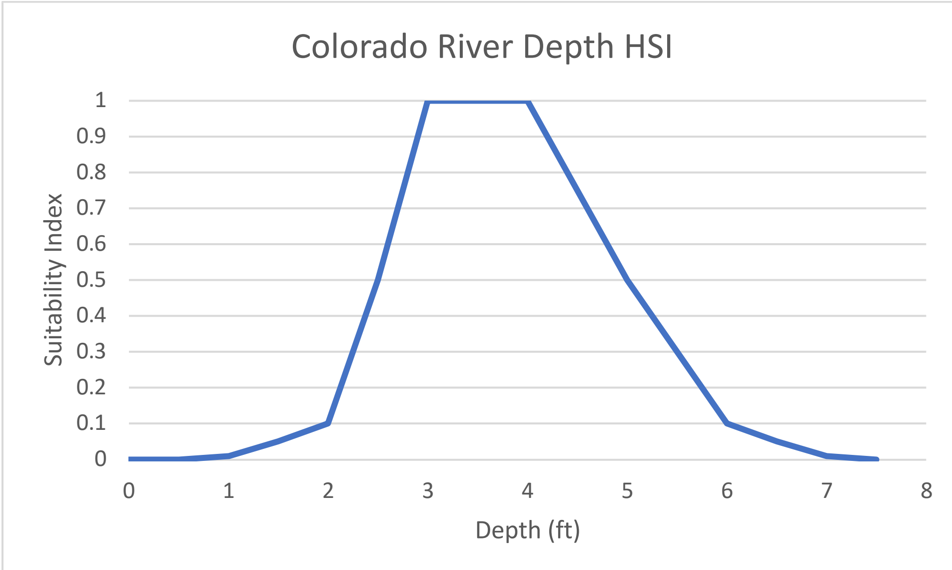

Figure 3. Depth Suitability Index for combined data set from Flannelmouth Sucker and Bluehead Sucker depth observations.

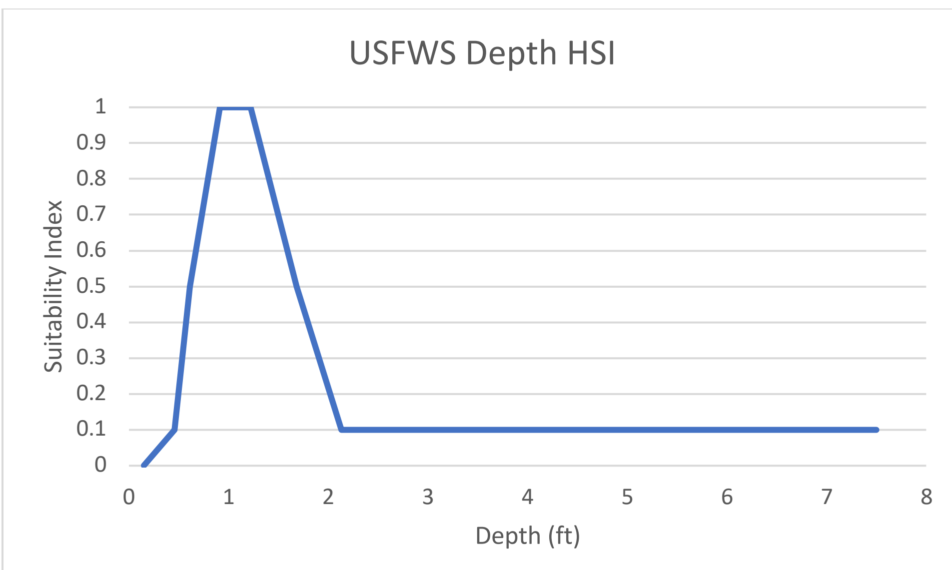

Figure 4. Depth Suitability Index for adult Flannelmouth Sucker from USFWS "FISHFIL".

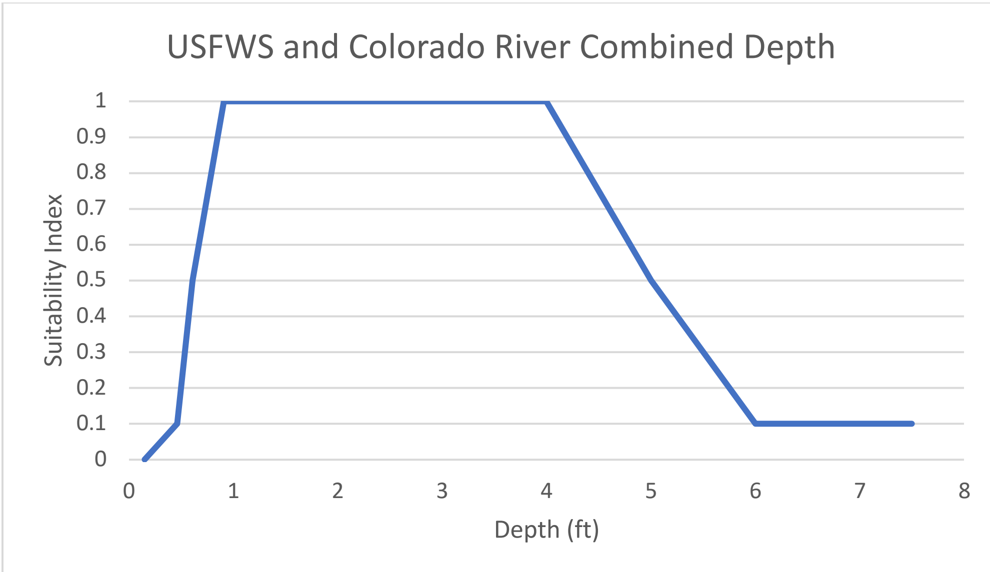

Figure 5. Depth Suitability Index for combined values from Colorado River depth SI and USFWS FISHFIL SI.

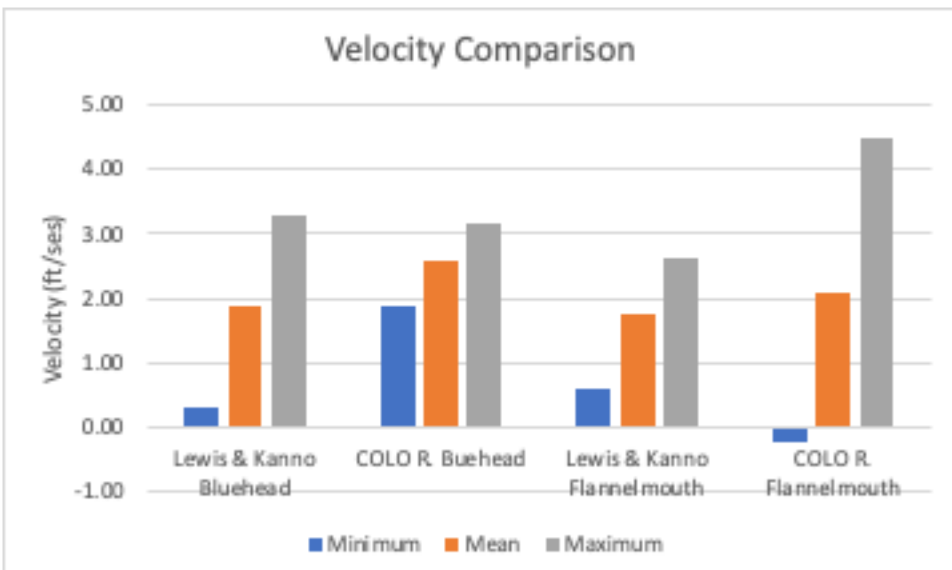

Figure 6. Comparison of velocities used by Flannelmouth Sucker and Bluehead Sucker.

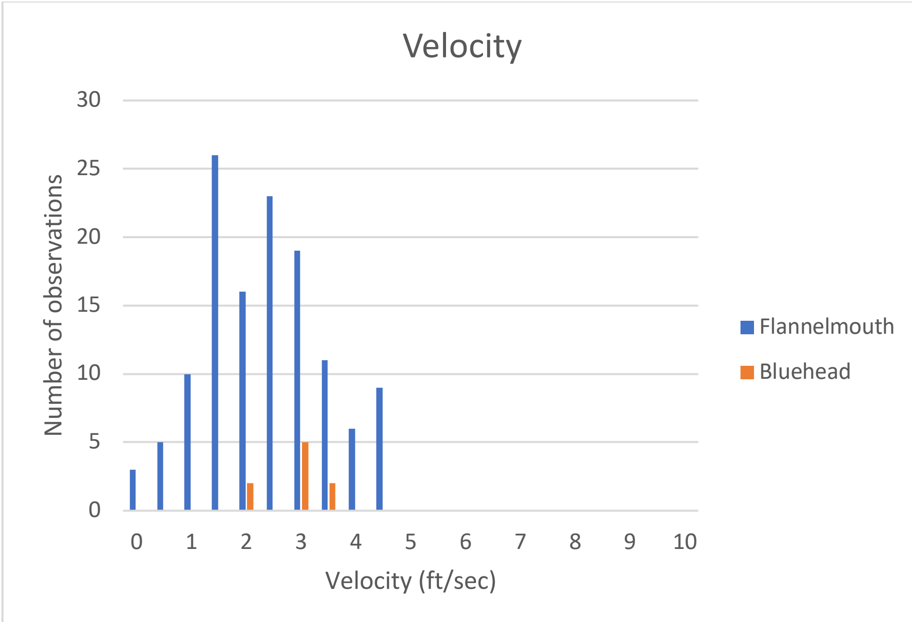

Figure 7. Colorado River velocity data for Flannelmouth Sucker and Bluehead Sucker. Source: Beyers et al. 2001 and Rees and Miller 2001.

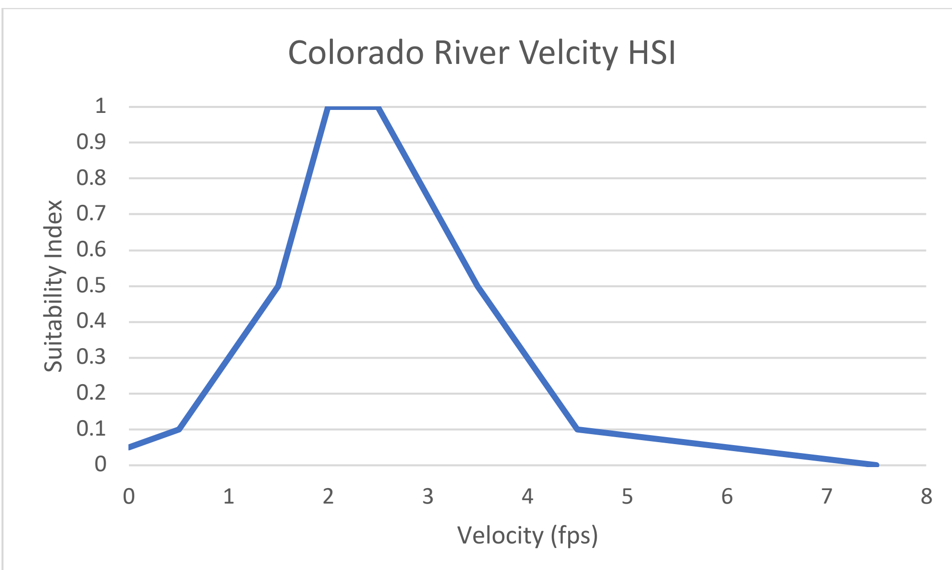

Figure 8. Suitability Index for combined data set from Flannelmouth Sucker and Bluehead Sucker velocity observations.

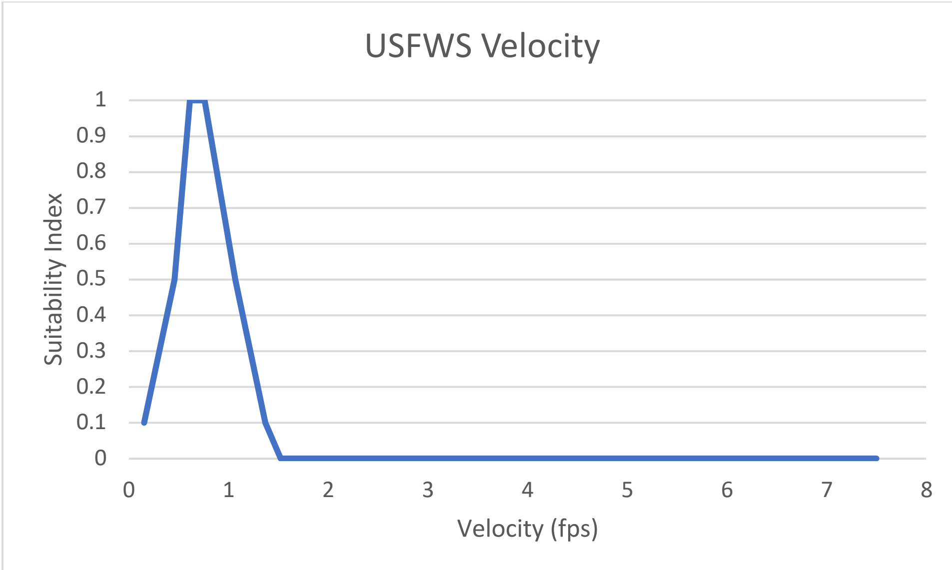

Figure 9. Velocity Suitability Index for adult Flannelmouth Sucker from USFWS "FISHFIL".

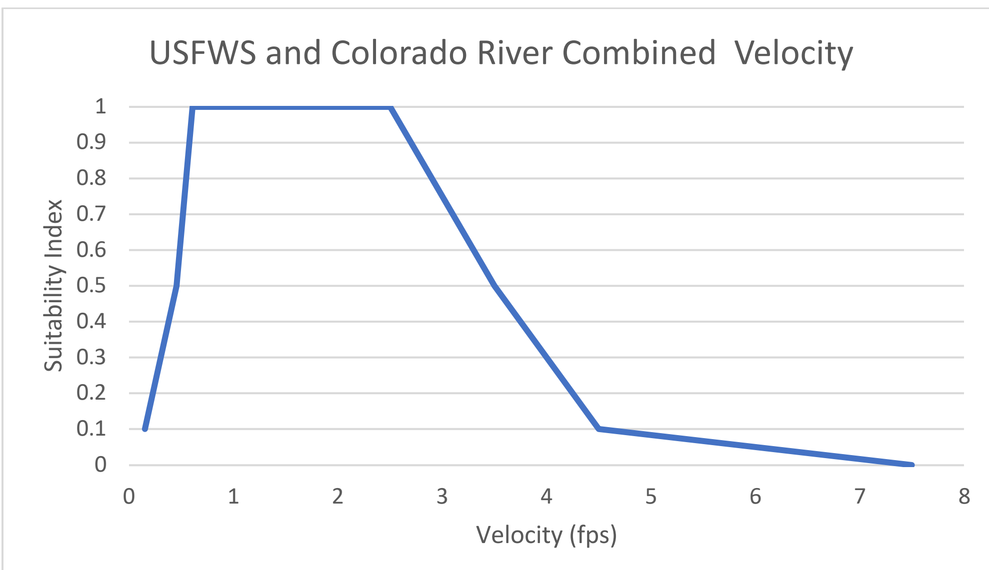

Figure 10. Velocity Suitability Index for combined values from Colorado River depth SI and USFWS FISHFIL SI.

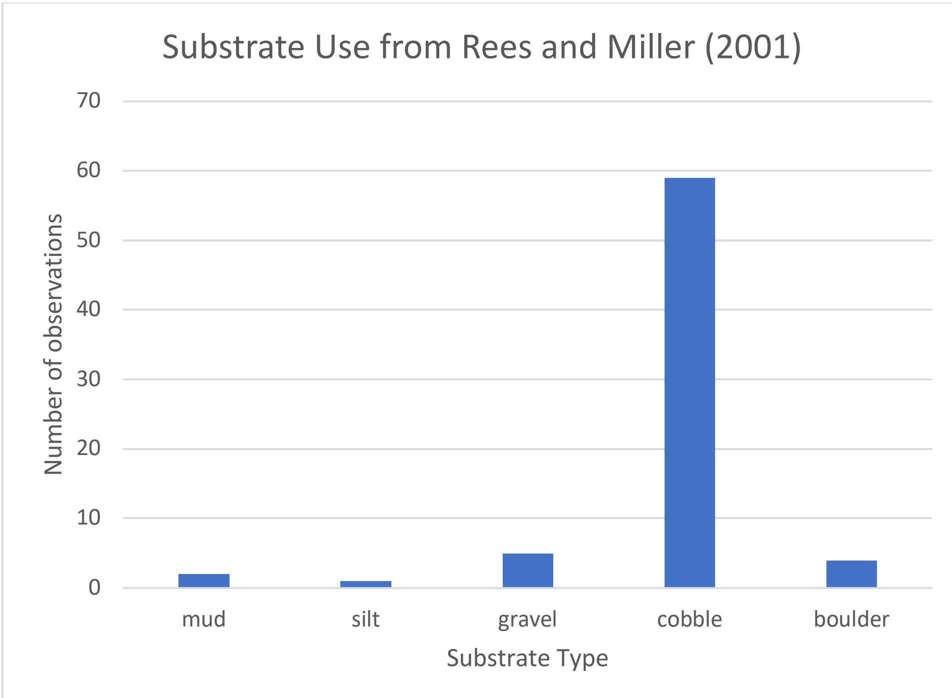

Figure 11. Substrate use observations from Colorado River; Source: Rees and Miller 2001.

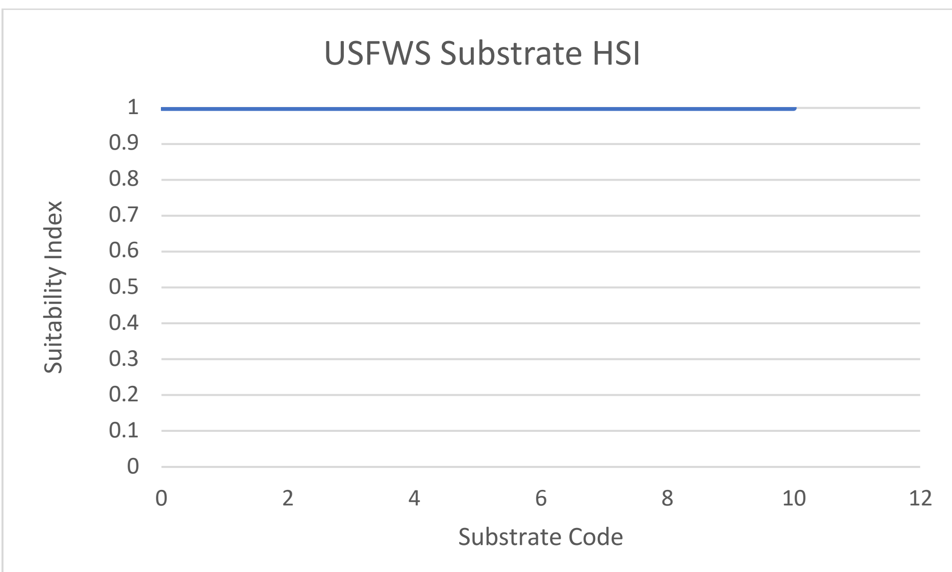

Figure 12. USFWS substrate suitability index from "FISHFIL" curve set.

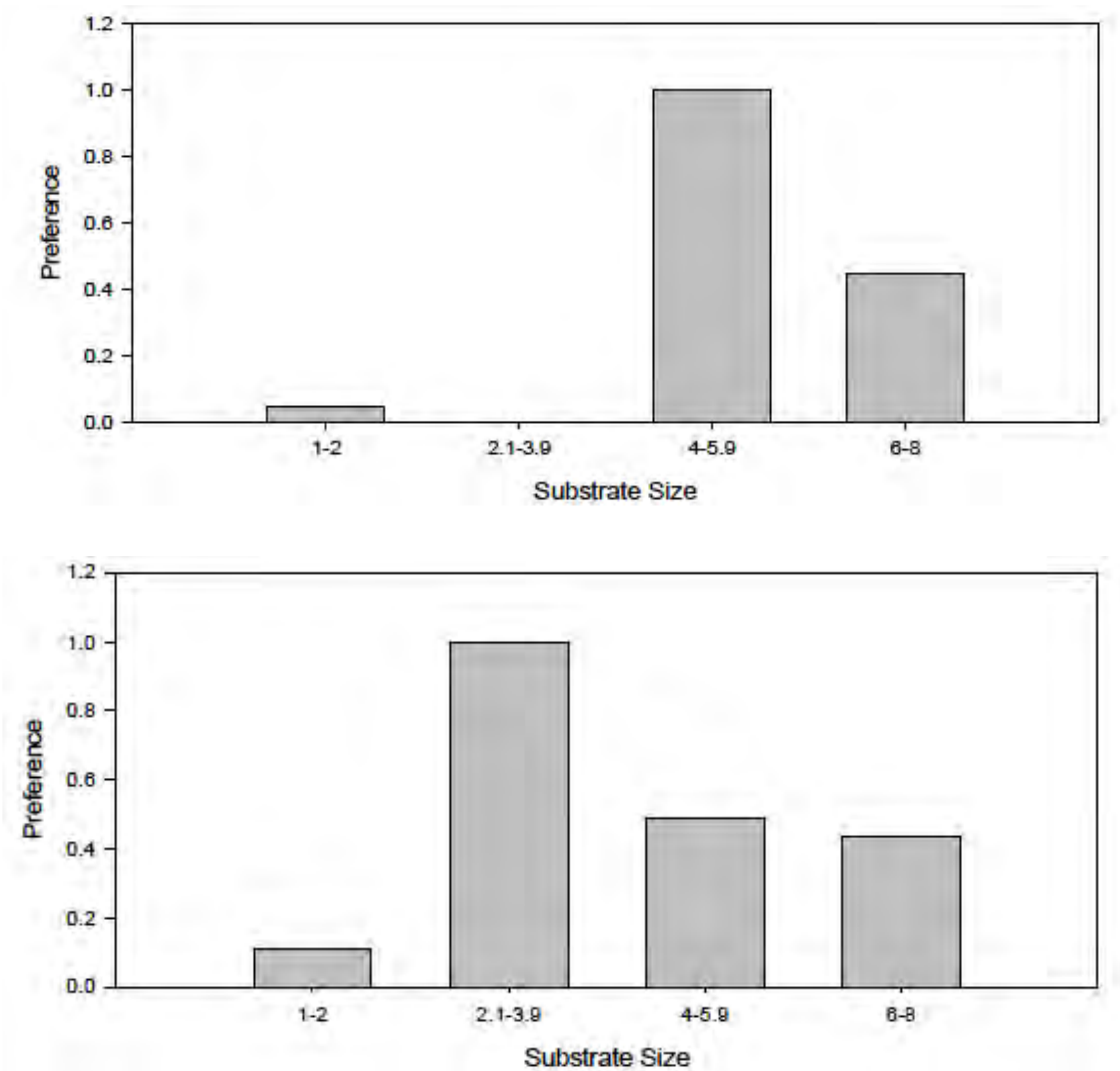

Figure 13. Substrate use for Bluehead Sucker (top) and Flannelmouth Sucker (bottom); Source: Bottcher (2009).

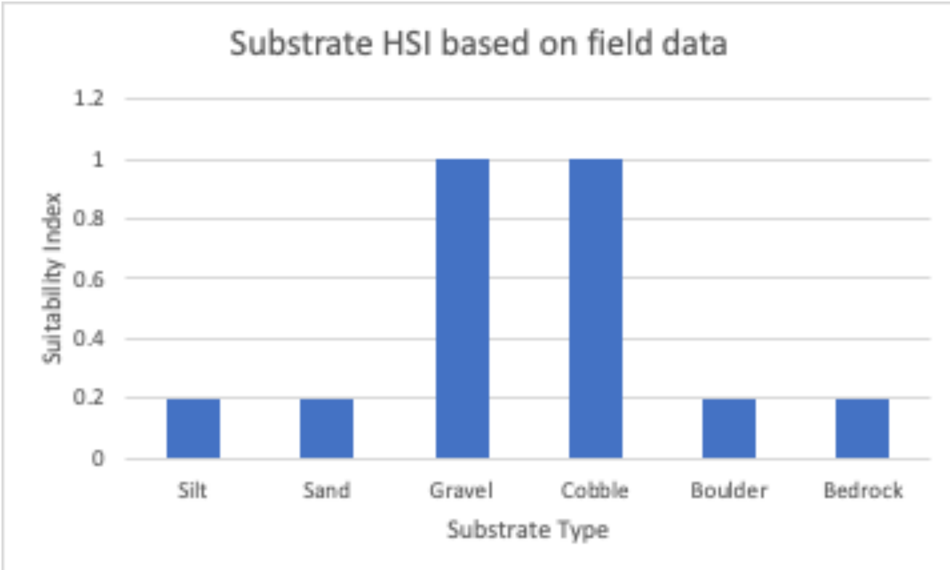

Figure 14. Proposed substrate suitability index based on field data collection.

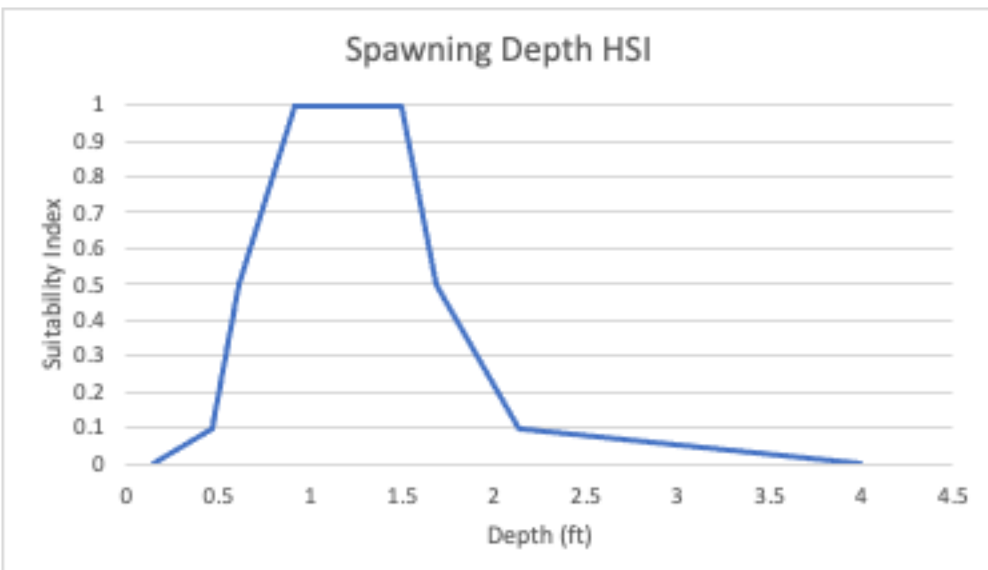

Figure 15. Proposed spawning depth suitability index based on life history traits and adult habitat use.

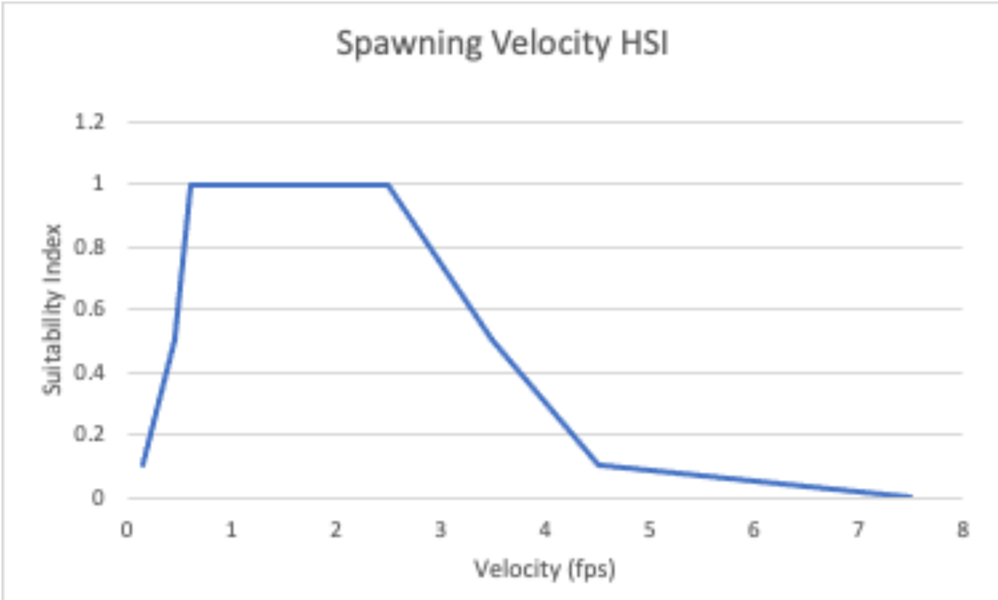

Figure 16. Proposed spawning velocity suitability index based on life history traits and adult habitat use.

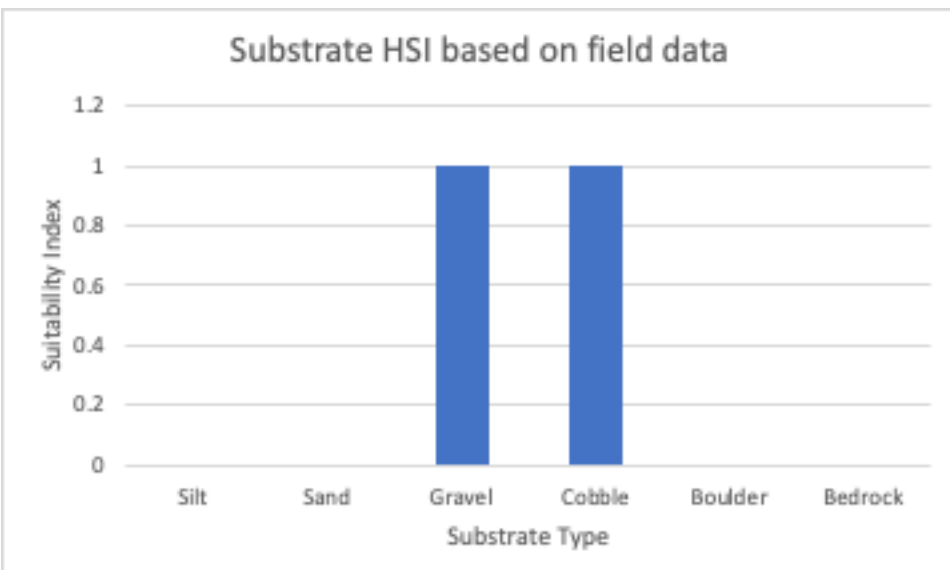

Figure 17. Proposed spawning substrate suitability index based on life history traits and adult habitat use.

Table 3. Recommended SI criteria for adult Flannelmouth Sucker and adult Bluehead Sucker in Milk Creek Instream Flow study.

Depth (ft)	SI value	Velocity (fps)	SI value	Channel Index	SI value
0.15	0	0	0.1	Silt	0.2
0.46	0.1	0.1524	0.1	Sand	0.2
0.61	0.5	0.4572	0.5	Gravel	1
0.91	1	0.6096	1	Cobble	1
3	1	2.5	1	Boulder	0.2
3.5	1	3.5	0.5	Bedrock	0.2
4	1	4.5	0.1		
5	0.5	7.5	0		
6	0.1				
6.5	0.1				
7	0.1				
15	0.1				

Table 4. Recommended SI criteria for spawning Flannelmouth Sucker and spawning Bluehead Sucker in Milk Creek Instream Flow study.

Depth (ft)	SI value	Velocity (fps)	SI value	Channel Index	SI value
0.15	0.00	0.15	0.10	Silt	0.00
0.46	0.10	0.46	0.50	Sand	0.00
0.61	0.50	0.61	1.00	Gravel	1.00
0.91	1.00	2.50	1.00	Cobble	1.00
1.50	1.00	3.50	0.50	Boulder	0.00
1.68	0.50	4.50	0.10	Bedorck	0.00
2.13	0.10	7.50	0.00		
4.00	0.00				

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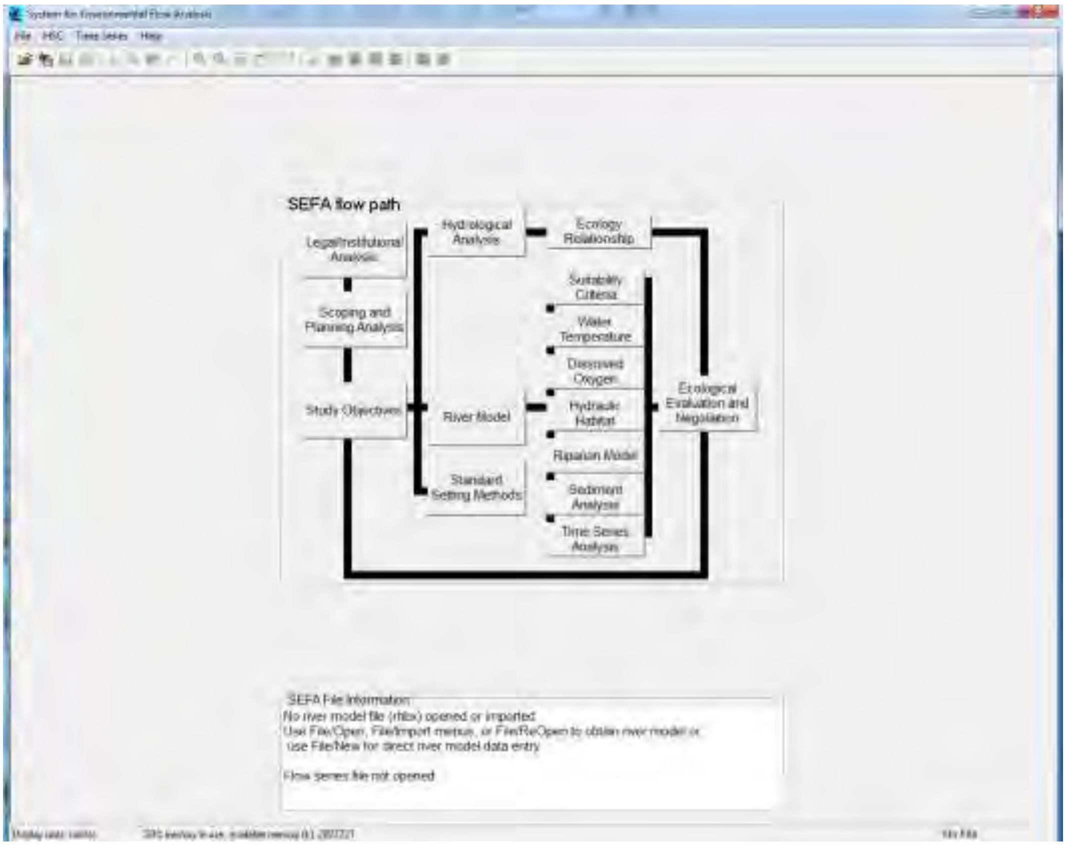
SEFA

System for Environmental

Flow Analysis



Software Manual

Version 1.9

I. Jowett

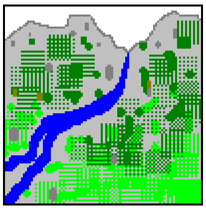
T. Payne

R. Milhous

May 2023

Contents

1 Introduction



SEFA was developed to provide ecologists, hydrologists, engineers and resource managers with an integrated set of tools for environmental flow assessment, as envisaged in the incremental flow analysis (IFIM).

- Improved instream habitat model,
- Development of habitat suitability curves and generalized additive models
- Sediment analyses, including flushing flows and sediment deposition,
- Water temperature modeling
- Dissolved oxygen modeling
- Time series analysis, including instream habitat, riparian inundation and indicators of hydrologic alteration

The program provides a set of tools that allows the effects of flow alteration on various physical parameters to be assessed. For example, the various outputs can be graphs or tables showing how parameters like area weighted suitability, dissolved oxygen, water temperature, inundation levels and sediment functions vary with flow. Changes to the flow regime can then be further examined using time series analysis to evaluate changes in the frequency, magnitude and timing of hydrological variables and variables such as area weighted suitability and inundation. The term area weighed suitability replaces the original weighted usable area (WUA) because it is a more accurate description of the physical meaning of the variable. The program does not make flow recommendations or set minimum flow or flow regime requirements.

2 Getting started

2.1 Installing program

The program can be installed on any PC with Windows 98 to 64-bit Windows 10 operating systems. A full installation requires about 22.2 Mb of disk space.

Run the install program. Administrator privileges are necessary for the install.

2.2 Installed files

The following files will be installed:

SEFA.EXE	Executable program
SEFA.LIC	License information for program
SEFA.CHM	Help file
SEFA.LIB	This is a library of habitat suitability curves. It can be developed by the user by importing curves from ASCII *.PRF, *.XLS*, or *.RCV files
HABSEL.EXE, HABSEL.CHM	Program and help file for development of habitat suitability curves and generalized additive models (GAMs).
Example data (optional)	Manual and examples

2.3 Program organization

Many of the analyses use data from a river model and the first operation will usually be to open or import data for the river model. Click 'File>>'Open' to open an existing SEFA **.rhbx** file or ReOpen to select a file that has been previously used. The panel below the flow path diagram displays the name of the file, its title, type and the number of cross-sections. The file name is also displayed in the bottom right panel.

The river modeling section of the program is organized so that the user moves from left to right during data input and analysis, starting with:

- importing xls, xlsx, txt, hab data (under 'File>>'Import'), existing rhb files for RHYHABSIM or RHABSIM or existing PHABSIM DOS (*.ifg) and windows files (*.phb etc.), entering data by keyboard (under 'File>>'New') or opening a previously saved file (under 'File>>'ReOpen'),

- checking (under 'Edit/Display>>'Check'), viewing and perhaps revising data (under 'Edit/Display>>'Edit/View'), although if data contains error it is advisable to correct the original data file that was imported, and to then import again,

- calibrating the model (under 'Hydraulic Calibration'), and finally,

- using the river model for available analyses ('Hydraulic Habitat', 'Sediment', 'Water Temperature', 'Dissolved Oxygen', 'Time Series').

Speed icons are provided for menu items that are used frequently, such as file open, import, export, print, cut, copy, paste, undo, zoom. Unzoom, graphical options, text display, cross-section plot, VDF (N values) edit, rating display, display all ratings, predicted velocities, hydraulic habitat analysis. Icons are enabled only when their use is allowed.

When any window is displayed a right click will also display menu options, such as copy to clipboard.

Development and viewing of habitat suitability criteria and time series analyses do not require a river model for their use and these analyses can be carried out without opening a river model (**rhbx** file).

3 Summary of SEFA Analyses

3.1 FILE MENU

3.1.1 New

This starts the SEFA data entry/edit module (File>>New or Edit/Display>>Edit/View), where it is possible to enter data directly. This form of input is not recommended. It is better to enter data in excel and import. In this way, you have a copy of the data in excel as well as in SEFA rhbx file.

3.1.2 Open

This opens an existing SEFA rhbx file. This file must have been created through the new or import functions. When a file is opened, the menu is expanded to show the various analysis menus. The file name is displayed in the bottom right of the status bar.

3.1.3 Import

This allows a text txt hab, excel xls xlsx, RHYHABSIM rhb, or RHABSIM rhb file, or existing PHABSIM DOS text (*.ifg) and PHABSIM windows files (*.phb etc.) to be imported. All the necessary data and calibration can be on the text or excel file. The files can be ASCII text (notepad or similar) in a *.hab or *.txt file, or excel file xls or xlsx. The ifg text file is an old fixed format text file used by the DOS version of PHABSIM.

If the imported data contains an error, the error line specified. You can correct the error in the original excel or text file and then import again.

Excel files

Only one sheet of the excel file containing the data is imported but other sheets in the excel file can be used to store other information (e.g., habitat mapping).

Two types of data entry are available in EXCEL files. The first emulates the text format in *.hab files. This requires attribute names and cross-section names to be in quotes (single or double), habitat mapping weights to have a percent sign and that a value (or na) is entered for every attribute at each cross-section data point. In EXCEL quotes (attribute and cross-section names) and % signs must be text. To avoid these restrictions and a second method of data entry can be used.

The second method emulates csv format. In this format, attribute and cross-section name quotes need not be used, but if used they will be ignored. The % sign for a habitat weighting value is not required but if used will be ignored. Values need not be entered for all attributes and a blank value is assumed to be zero. **Attribute values must be in the same column at their respective attribute name.**

The important distinction between text and csv excel formats if that with text more than one value or names can be in a single cell. **With the csv format, ever value of name must be in its own cell.**

Cross-section data

Cross-section data can be in terms of water depth or elevation (RL reduced level). Using RL allows the input of “dry” cross-sections.

Missing values for offset, depth, velocity, revs, time and attributes can be specified as na. Linear interpolation is used to estimate missing values. Linear interpolation may not be appropriate for some attributes, such as those specifying percent substrate type or point specific features such as cover.

Missing values in multi-point velocity measurements are not allowed.

3.1.4 Load commands

This allows batch processing for the analysis of multiple rhbx files (100+). The batch file .cmd is a text file with its own specific format as described in the help manual.

3.1.5 ReOpen

This lists files that have been opened or imported. If one of these is selected it is opened or imported as appropriate. This avoids navigating the windows Open file dialog.

3.1.6 Save as

This menu item shows when a file is opened and allows the SEFA rhbx file to be saved with a different name.

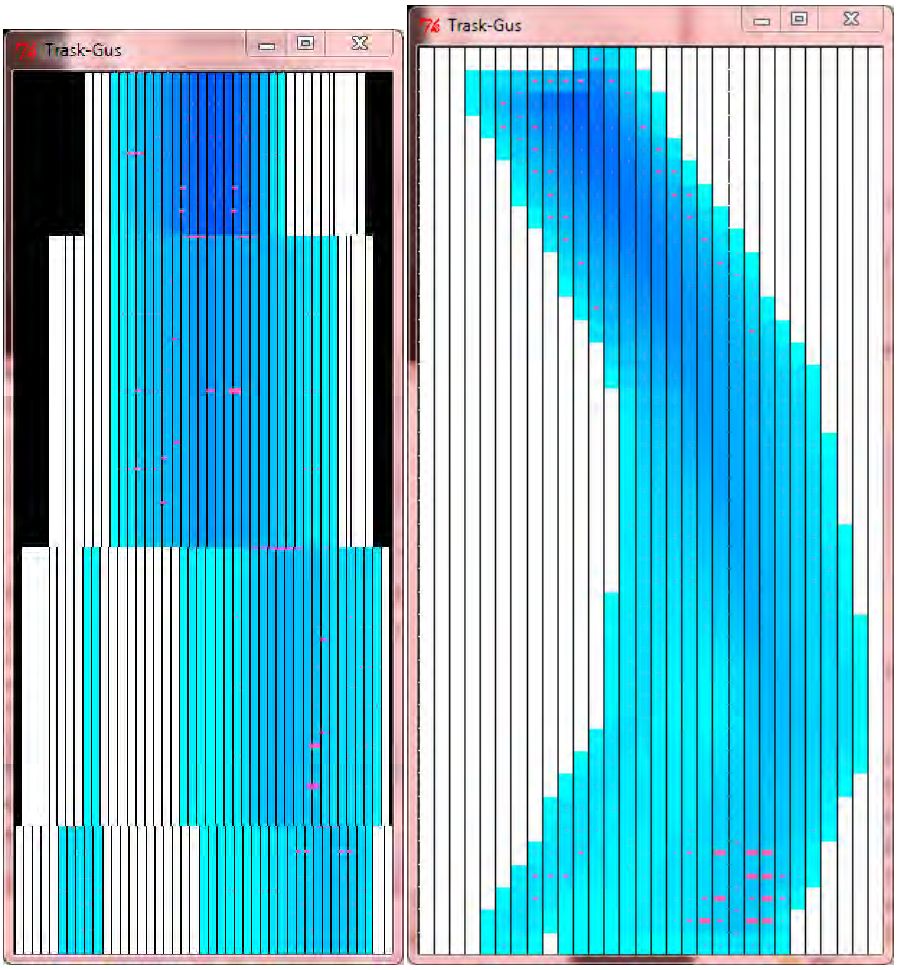
3.1.7 Export

This allows a .rhbx file to be exported as a text file (.hab, .con, .vdf) or as data suitable for import into inSTREAM.

The text (.hab, .con, .vdf) files could then be imported to recreate the rhbx file. This is useful for creating a text backup of a file and its calibration. It also provides an alternative method of viewing the data, when you are familiar with the text format.

Two files are exported for inStream; one containing the geometry of the cells and the other containing the predicted depth and velocity in each cell. Subscripts are added to the filename specified "_CellGeometry.dat” for the geometry data and "_HydraulicData.csv" for the hydraulic data.

The definition of the data exported will depend on whether the reach is a representative reach or habitat mapped.



Example of inSTREAM output for habitat mapped reach (left) and representative reach (right).

3.1.8 Preferences

Calculation

Methods for calculating hydraulic habitat can be changed here. The default methods are recommended for general use, but preferences can be set to allow an emulation of IFG4 Manning's N calibration and calculation of velocity.

By default, SEFA calculates habitat suitability by interpolating linearly at between cross-section measurements points. For example, if one point is measured at the water's edge and the next in the water at a depth of 0.5 m, the program will calculate habitat suitability at 0.025 m increments from 0 to 0.5 m. If this is not checked, habitat suitability will only be calculated at measurements points, as it was in PHABSIM. In some cases, linear interpolation of attributes may not be appropriate and check boxes allow linear interpolation of depth and velocity with the attributes at the measurement point.

Log-log rating relationships are derived for stage-discharge pairs of measurements. The default method is to fit the curve through the survey flow and the best least square fit to other stage-discharge pairs. This method is most appropriate if the survey cross-section is based on measured water depths, because it does not introduce spurious depth errors in depth when predicting water levels at the survey flow.

The alternative method is that used in IFG4 (PHABSIM) to fit the curve through all stage-discharge pairs. This is most appropriate where bed levels rather than water depths were measured at the survey flow,

The default velocity calibration and prediction method is to calculate Manning's N and VDF from conveyance (a function of hydraulic radius) at measurement points. When predicting velocities for a given flow, they are calculated from conveyance and are then adjusted so that the they give the given flow times the ratio of measured to survey flow. Using this default method and the default log-log rating method predicted velocities at the survey flow will be the same as measured velocities.

The alternative method is that used in IFG4 (PHABSIM), where Manning’s N values are calculated from water depth and velocity at each measurement point and the slope for the cross-section (usually the default slope of 0.0025). When predicting velocities for a given flow, they are calculated using manning’s equation (N, depth and slope), with the velocities are then adjusted so that they give the given flow.

Calculation of habitat suitability. Three methods of calculating the combined suitability index are available. The default is for CSI values to be multiplied to form a single combined index. In the default method, habitat suitability is calculated at the measurement points and at 10 linearly interpolated points between measurements. The alternative (PHABSIM) method is to calculate the suitability at the measurement point and assume that it applies between the mid-points of adjacent measurement points (i.e., a cell).

When a water level is higher than the left or right bank, the water edge is estimated by linear extrapolation. However, if the bank slope is less than 0.05 (the default), a vertical bank is created. PHABSIM always creates vertical banks.

Stage discharge relationships calculated using Manning’s equation (MANSQ) can assume that hydraulic roughness varies either with discharge or hydraulic radius. The default method is to allow roughness to vary with discharge. This choice usually has little effect on rating curves.

When calculating a water surface profile, the conveyance can be calculated in two ways. A combination of Harmonic and arithmetic mean is the default method. This rarely has much effect on water surface profiles.

Text font

Results are usually displayed graphically. If results are displayed graphically, the text version of the results can also be displayed by clicking on Edit Display>>Show as text. The set text font specifies the style and size of font used to display text.

Units/Date

Presentation units can be selected. Internally, all calculations are carried out in metric, but results can be presented either in feet or metres. When files are imported, the units of the file will be requested, if not specified in the file.

The default date/time presentation format is day/month/year order. It can be changed to month/day/year order by checking US date format.

Decimal places

The number of decimal places displayed in output can be set.

3.2 EDIT/DISPLAY MENU

3.2.1 Check

This is one of the most important functions. It provides a check of the data and calibration. The results are listed in a text window and if there are any problems, they are shown as blue text. There are quite a number of checks. These include:

- checking substrate names that are entered against the substrate categories that that the program assumes.
- Checking rating curves.
- Checking levels.
- Checking gauging.
- Checking that % composition of substrate categories sum to 100%.
- Checking for extreme of negative values of velocity.
- Checking that offsets are all in increasing or decreasing order.

One of the most useful is the check of calibration gaugings. Here the stage change/flow change is tabulated and exceptionally high or low values are highlighted as possible errors.

3.2.2 Edit/View

This opens the data entry/edit model. On a series of tabs it lists the cross-section summary, the attributes (substrate etc.) associated with each measurement point), the cross-section points (offset depth etc.), the calibration gaugings and stage zero flow with a thumbnail sketch of the rating.

If the file is a representative reach (see Section 4.1), the reach geometry is also shown. This can be altered either graphically, entering the coordinates of cross-section start and ends or by entering bearings and distances.

There is the facility to comment each measurement point, cross-section, and reach, to select the habitat type of each section, and to specify detailed geometry (for 2D type display).

A habitat mapped reach can be converted to a representative reach by clicking the representative reach button and vice versa.

3.2.3 Flows

This calculates and displays a table of the flow, depth, velocity area and energy coefficient at each cross-section and the average of all. The average of the flows is the default estimate of the survey flow (best flow). This is overridden if the survey flow is specified in the input file.

3.2.4 Cross-sections

This is usually used to check for errors in cross-section data.

It produces a graph of each cross-section showing the depth (or level), offset, velocity and SZF (Section 4.2). The graph options allow the display to be altered (depth/level, text, symbols, colors, axes, legend etc.)

A click on any point on the graph will show the values at that point.

3.2.5 Display

Longitudinal profile

This is enabled when the file is a representative reach. It shows the water surface elevation, and mean bed elevation versus distance upstream. Options allow maximum bed elevation, bank elevations, and calibration gaugings to be shown.

Isometric view

Provides a pretty display with options that allow it to be rotated.

Plan

This produces a pseudo 2D view of the reach for representative reaches and a simplified (i.e., no longitudinal variation between cross-sections) view for habitat mapped reaches. The layout of the reach is specified in the Edit/Display>>Edit/View menu item. If the graph looks strange, check Edit/Display>>Edit/View and set bearings of cross-sections so that they are (roughly) 90 degrees to the bearing to next section.

The default display is for the survey flow. Minimum, maximum, and mean values of depth, velocity, substrate size, shear velocity, attributes and habitat indices are tabulated on the left of the display. Clicking on any one of these items will show that item on the graph, with contours and shading. Clicking at any point on the plan will give coordinates and values of all variables.

Interpolation uses streamlines to divide the river laterally.

Options allow for the number of transverse streamlines and longitudinal divisions (compartments) to be set. The contour interval can also be set. Shading colors are from blue to red, with blue representing the highest value and red the lowest.

If the flow value at the top left of the window is altered, the plan is recalculated for that flow.

A range of flows can be displayed successively by setting a minimum, maximum and interval and pressing the Flows button.

The color range and grid scale for each flow can be fixed in Graph Options so that the same color gradient and range is used for all flows.

A right click on the graph shows options for the export of these data. Basically, the data can be exported to the clipboard as XYZ coordinates with calculated values at each XY point. (XY points are determined by the transverse and longitudinal streamline grid. The drift model output specifies data in the form needed for John Hayes Drift model[1] and has an estimation of the vertical velocity distribution with the XY coordinates.

RHBX File Contents

A SEFA file contains the river model file, as well as other components storing the calculation options for that file, the last set of flows used for calculations, and AWS-Flow relationships that have been saved.

The file component "SEFA.RHBX" contains the river model data. The component "preferences.ini" contains the calculation preferences, the component "PRFS.RPF" contains the habitat suitability curves, the component "FLOWS.RPF" contains the flows that have been specified for the last calculation, and the components "AWSFLOWS_date_time" contain the AWS/flow relationships that have been saved.

The components preferences.ini, PRFS.RPF, FLOWS.RPF and AWSFLOWS_date_time can be deleted using Edit/Display>>RHBX File contents, although this should only be required to delete saved AWS/Flow relationships that are no longer required. If preferences.ini is deleted Calculation preferences will be replaced by default values. If PRFS.RPF is deleted, no habitat suitability curves will be associated with the file.

File information (Notes) can be viewed and edited in the Edit/Display>>RHBX File contents menu.

3.2.6 Graph Options

The graph options allow the graphs to be changed so that they are suitable for copying to documents using the clipboard and windows metafile formats. The options available vary with the graph displayed. In most, it is possible to change the axes scales, tick marks, Axes labels, graph title, legend, symbols, line width, and colors.

[1] Hayes, J.W.; Hughes, N.F.; Kelly, L.H. (2007). Process-based modelling of invertebrate drift transport, net energy intake and reach carrying capacity for drift-feeding salmonids. Ecological Modelling 207: 171-188.

The vertical dimension can be displayed either in terms of water depth or water level (elevation).

Options can also change what is displayed on the graph. For example, when a rating curve is displayed, the default is the rating fitted through the gaugings and SZF. If you want to display other ratings (curve with best estimate of SZF, hydraulic (ManSQ), critical flow, rating through modeled WSP profiles), you select the type of curve to display. Similarly, you can also display the multi-channel flow rating which shows the flow in channel versus total river flow. You can also display the relationship between Manning's N and flow that is used in the hydraulic rating (ManSQ).

3.2.7 Show as text

This very useful function displays a text window containing the data that are used to display the graph. The data shown are for the whole analysis that was carried out and not just the portion displayed in the graph. Some graphs do not have this option available. For example, when cross-section data are plotted the show as text menu item is disabled because the data is on the original data file or can be obtained or viewed in other ways (e.g., Edit/Display>>Edit/View or File>>Export).

3.2.8 Zoom

This changes the cursor to a hand pointer and any portion of the graph can be displayed by holding down the left mouse key and dragging the selection box so that it contains the area you want displayed. The graph is then displayed showing only the selected area.

3.2.9 Unzoom

This "undoes" all zooms and returns the graph to the default axes.

3.2.10 Cut, Copy, Paste, Undo

When a text or graphics window is actively displayed, the only valid action is copy. This will copy the entire text or picture to the clipboard. This can then be pasted directly into a document (as windows metafile for picture) or into excel. In excel each table item in the text is a cell in excel.

3.3 HYDRAULIC CALIBRATION MENU

3.3.1 Set survey flow

The survey flow is the best estimate of the flow in the cross-section when the survey was carried out. The default is to set the survey flow as the arithmetic average of the flows calculated for all cross-sections. This is overridden if the survey flow is specified in the imported file. Survey flows can be set for the whole reach or for individual cross-sections. When the survey flow is altered the ratings and velocity distribution factors (VDFs or point Manning's N values) are recalculated automatically.

3.3.2 Ratings

Display section ratings

This and the next item are essential menu items that allow ratings curves to be checked.

The section rating shows as a graph of stage versus discharge with the survey flow and calibration gaugings shown. All available rating types are shown initially, but what is displayed can be changed in Edit/Display>>Graph options. A click on any point on the graph will show the stage and discharge at that point.

A set of buttons on the bottom of the window are used to change the cross-section that is displayed.

Display all ratings

Rating curves for all sections are shown on a log-log scale. Usually the ratings will form a pattern of gradually converging lines. If a rating departs from this pattern by crossing other ratings, it may indicate an error in the rating.

An individual rating can be identified by clicking on the rating and the name of the cross-section will be shown.

The ratings fitted through gaugings and SZF are shown as the default. Other rating types can be shown by selecting the rating type in Edit/Display>>Graph options.

Each cross-section does not necessarily use the same rating type for analyses that are carried out (see Select ratings below). The ratings selected for use can be displayed together.

Rating curves can be edited (arbitrarily) by clicking the button at the bottom of the window. This displays the relevant rating parameter (e.g., the exponent of the rating equation).

Edit ratings

Rating curves for all sections are shown on a log-log scale, with straight lines joining stage-discharge measurements.

Individual rating can be identified by clicking on the rating and the name of the cross-section will be shown. The ratings that are displayed can be selected using the button on the bottom of the window.

Rating curves can be edited graphically by left clicking on a stage-discharge value and dragging up or down to alter stage. Flow can be altered with a **Shift left button** click and moving to the left or right. The SZF can be altered with a **Ctrl left button** click and moving the rating up or down. After movement, the amount of change is displayed.

Edit rating exponents

Rating curves can be edited (arbitrarily). The exponent of the log-log ratings, the beta value of the hydraulic ratings and exponent of the log-log WSP ratings are displayed and can be changed.

Select ratings

The default rating curve is the rating fitted through calibration gaugings and SZF. If there are no gaugings, the default rating is the hydraulic rating assuming that Manning's N is constant.

Each cross-section does not need to have the same rating type for analyses that are carried out. The Select rating menu item allows the default to be changed for all sections (by selecting all cross-sections in the dialog), or you to select the appropriate types of rating for each cross-section.

Recalculate ratings

This recalculates default ratings for all cross-sections.

3.3.3 Velocity Distribution factors

Edit Velocity Distribution Factors

Velocity distribution factors (VDFs or point Manning's N values) are calculated automatically. The assumption is that VDFs at the water's edge or above water level are the same as the nearest measurement point in the water. The VDF is the ratio of the measured velocity to the velocity calculated assuming uniform flow conditions where the point velocity is proportional to the conveyance at that point. If the flow is uniform, the VDFs will be 1. The magnitude of the VDFs can indicate errors in measured velocities.

The VDFs or N values are displayed as values across the transect and can be edited graphically by clicking on a value and dragging it up or down to a new value.

Reset recalculates default values for VDFs.

Reset Velocity Distribution Factors

Reset recalculates default values for VDFs and Manning N values.

Edit Beta Values and Reset Distribution Factors

A beta value can be introduced to represent the way in which roughness (Manning's N and VDF) changes with discharge. The beta value can be different for each cross-section, although usually they would all be set to the same value. Usually, the roughness will increase as the depth or hydraulic radius decreases. A beta value of 0 assumes that roughness does not change. A value of -0.3 assumes that roughness increases as depth decreases. Experience shows that the roughness near stream edges is usually greater than in the deeper parts of a stream. A value of -0.3 is recommended for beta, although the default value is 0. A negative value for beta helps solve the velocity distribution problem, where predicted velocities near the edge are often too high.

Once beta values have been changed Manning Ns and VDFs are recalculated.

3.3.4 Velocity pattern

This produces a graph showing velocities across the cross section for each flow modeled. Arrow buttons scroll through sections.

The effect of different VDF or Manning N assumptions of velocity distribution can be examined with Hydraulic calibration>>Velocity pattern. When the distribution of velocity is displayed, Shift F1 will toggle between VDFs applied and best VDFs, Shift F2 will toggle between VDFs applied and VDFs not applied.

This graph is useful for checking that velocity predictions are consistent. For example, errors in the low flow part of ratings can reduce the water level and cross-section area so that it appears as if the velocities increase as the flows reduce. Although this is hydraulically possible, it is unlikely and a sign of poor ratings.

Show as text tabulates measured depth, velocity and modeled depths and velocities for each flow and cross-section.

3.3.5 Water Level Predictions

This produces a graph of predicted water levels versus distance for modeled flows. This is used to test rating curve predictions. Normally, the increase in water level should be relatively consistent through a reach, resulting in a uniform pattern of water level profiles along the reach. Where water levels at each cross-section are referenced to a common datum, the water level at each cross-section should be less than the water level at upstream cross-sections.

3.3.6 Velocity Adjustment factors

This displays Velocity Adjustment Factors (VAFs) versus flow for each cross-section.

3.3.7 Water surface profile

This WSP module is only applicable to representative reaches, where the bed and water levels of each cross-section are referenced to a common datum, the distances between cross-sections are specified, and the cross-sections are sufficiently close together to meet the assumptions of a water surface profile model (i.e., that there is uniform variation of water surface and cross-section properties between cross-sections). Predicted water surface profiles can be saved and used to develop log-log stage discharge relationships. The predicted water surface levels can also be displayed in the form of rating curves.

Fit roughness coefficients

This is the calibration menu item and it displays the reach/cross-section calibration in a spreadsheet format. Calculation of Manning's N and beta values between cross-sections is automatic. Beta values describe how Manning's N varies with discharge and are the slopes of the log-log relationships between Manning's N and discharge.

The various items on the spreadsheet are adjusted until an acceptable set of values of N are calculated. The main value that is adjusted is the stage adjustment. This raises or lowers the elevation of the cross-section. The justification for adjusting elevation is that heights of a mm or so can have a strong influence on values of Manning's N and the field measurement of water surface elevation is not that accurate. Bend expansion and contraction losses can be set by double clicking "Other losses". Values of Manning's N can be entered arbitrarily, if required.

If a hand displays, a double click will display more information. If the text is selected when you click on a cell, it means that that text can be edited.

Calculate WSP

This displays the longitudinal profile of the reach (water surface and mean bed elevation versus distance upstream (same as Edit/Display>>Display>>Longitudinal profile).

To calculate a WSP, click the model button to display a dialog that allows you to set the flow to be modeled and water level at the downstream section. The default is the survey flow and the surveyed water level at the downstream section. If the default calibration has been saved, modeling the WSP with the survey flow and level will reproduce the measured flow profile. The predicted water surface profile is shown as a yellow line. This profile can be stored by pressing the Save button. This changes the color of the line to black and will retain that profile when you model other flows.

It is possible to start modeling (in upstream direction) at cross-sections other than the first. It is also possible to calculate the WSP using additional cross-sections interpolated between the measured cross-sections. In some cases, this results in a more realistic profile.

Modeling options allow the flow to be varied through the reach.

It is possible to automatically change Manning's N with flow. There are a number of ways of doing this (e.g., use the beta value of the first section for all, use the calculated beta between each pair of sections, use the average beta value for all).

If WSP profiles are calculated and saved for a range of flows, the predicted water surface levels can be displayed in the form of rating curves. When the window is closed you are asked whether you want a rating curve to be fitted to the saved water surface levels at each section. This is the WSP rating and it can be used for subsequent analyses (See Select rating).

3.4 HSC

3.4.1 Select suitability curves

This menu item will import habitat suitability curves from a library file, display HSC that are in a library file, and select habitat suitability curves from a library file for use in subsequent habitat analyses. The selected curves are stored in the file that is open, so that a rhbx file must be open before HSC can be selected.

Habitat suitability curves are shown graphically by double clicking any HSC title. Show as text gives the numerical values that define the curves and the arrows at the bottom of the window can be used to scroll through the habitat suitability curves.

Habitat suitability curves are imported from text files into a library. It is possible to have multiple libraries with different names (*.lib) in different directories.

The import button selects the text file for importation into a library of habitat suitability curves. When this is done, there is a choice to merge the HSCs with the existing file, to replace the existing library, or to save the curves in a library with a different name.

The Select Library button allows a different library to be selected (i.e., a *.LIB file held in a different location in the computer).

3.4.2 Select statistical model

Imports statistical models (GAMs) developed in the HSC module or MOPED (freeware which can be downloaded from www.jowettconsulting.co.nz) into the habitat suitability library for use in habitat analyses. These are usually generalized additive logistic or Poisson models, but other model types are possible. When the model is imported, Select habitat suitability curves (see above) can be used to display the GAM graphically by double clicking on it.

3.4.3 Develop HSC

This opens a module for the analysis of habitat suitability measurements and the development of habitat suitability curves and generalized additive models (GAMs). Measurements of fish presence/absence or abundance plus the habitat characteristics (e.g. depth, velocity and substrate) are required to determine habitat selection (suitability) and GAMs.

Observations of species presence/absence or density and hydraulic habitat parameters are imported from text or xls files and suitability curves derived. The curves can be exported as text and edited to create suitability criteria in *.prf or *.xls files suitable for import into a habitat suitability curve library (*.lib). Generalized additive models can be developed and saved for use in SEFA.

3.5 HYDRAULIC HABITAT MENU

3.5.1 Geometry

Section hydraulic properties

This gives graphs and tables of the hydraulic properties (area, hydraulic radius, width wetted perimeter) of each cross-section. The area is displayed first and the others can be selected using the select button on the bottom of the window. Normal display options are available (depth/level, text, symbols, colors, axes etc.)

Reach area/volume

This is enabled when the file is a representative reach. It is for calculating the area and volume of lakes. It shows the water volume of the reach, assuming a horizontal surface. The Surface area is displayed using the select button on the bottom of the window.

3.5.2 Reports

Statistics

This lists as text details of the survey, such as the total number of measuring points in and out of water and their average spacing.

Calibration

This produces a detailed report on the survey calibration.

Summary

This produces a detailed report on the survey. It lists details of the survey along with any comments.

3.5.3 Measured

This module analyses the river model data in the rhbx file as “measured” (i.e., as entered without any prediction).

Cross-section

This produces a graphical display of the variation of habitat, velocity, Froude No, Velocity*depth, and attributes (e.g., substrate) across each cross-section.

Arrows at the bottom of the window scroll through the cross-sections. The Select button can select the variable that is displayed.

Show as text lists tables of each cross-section and habitat, velocity, Froude No, Velocity*depth, and attributes (e.g., substrate) at each point.

Reach

This produces a text summary of weighting, flow, depth, width, velocity, area, wetted perimeter, Froude No, Velocity*depth, pool, run, riffles% and the dominant habitat type for each cross-section and summed over the reach. Similarly, for the attributes and habitat (AWS and CSI). A two-way table of depth and velocity shows the distribution of depth/velocity measurements.

The summary table can be produced for any combination of reaches and cross-sections using the Reach and Section buttons. The Reach button allows other rhbx files to be selected for analysis. When multiple files are selected they can be combined (e.g., total habitat in both reaches) or processed sequentially (results are tabulated for the first reach and then the second reach). The Section button allows sections to be excluded from the analysis.

This facility for multiple reach and section selection is provided in many of the following analysis items.

Passage

This produces a text summary of passage width (using limiting depth and velocity criteria) at each cross-section and through the reach.

3.5.4 Predictions for

All of these menu items predict variation with flow using selected rating curves. Most of the analyses can be carried out for any combination of reaches and cross-sections using the Reach and Section buttons. The Reach button allows other rhbx files to be selected for analysis. When multiple files are selected they can be combined (e.g., total habitat in both reaches) or processed sequentially (results are tabulated for the first reach and then the second reach). The Section button allows sections to be excluded from the analysis.

Flows to be modeled can be specified in 3 ways.

1. from a minimum to maximum at a specified interval
2. enter flow values in a table at unequal intervals if required, and
3. entering level flow pairs for each cross-section.

It is possible to model different flows for each cross-section and for each reach, if multiple reaches are selected.

This allows an analysis of two reaches to take into account any tributary flows that occur between the two reaches.

The first time that a range of flows is modeled, the default flow range is used. The default flow range is calculated to give a range of flows based on a reasonable extrapolation of rating curve from 0.5 times the minimum of the survey and calibration flows (Qmin) to 2 times the maximum of the survey and calibration flows (Qmax). Qmax and Qmin are then rounded for plotting with a default interval of (Qmax-Qmin) divided by 10.

By default, habitat is evaluated using depth, velocity and substrate criteria. It is possible to use any combination of these criteria. In addition, other criteria such as a substrate index or cover index can be included in the evaluation, but suitability curves for the other criteria must be included the suitability criteria and the index included in the river model file as an attribute.

When a reach has been modeled, the AWS/Flow results can be saved, not as a separate file, but as part of the SEFA file. The suffix of save AWS/Flow results is the date and time, so that it is possible to save a series of results. The calculations options used to produce the results are also saved and can be viewed if the results are subsequently used as an overlay or when applying and AWS/Flow relationship to a hydrological time series.

If AWS/Flow relationships have been saved, either in the SEFA file that is open or another SEFA file, those relationships can be overlaid on the AWS/Flow graph that is displayed. Hydraulic habitat>>Overlay AWS/Flow relationship or right click on the graph window and select Overlay AWS/Flow relationship. All saved relationships are displayed along with their calculation details. Select one and click OK.

By default, the velocity distribution is calculated using the VDFs or Manning N values. This can be switched off so that velocities are calculated using the conveyance or Manning N method (i.e., the VDF or Manning N is the same at each point).

Point

This produces a graph showing habitat, velocity or Froude No across the cross section for each flow modeled. Arrow buttons scroll through sections and the select button is used to select the variable that is displayed.

Show as text tabulates for each flow and cross-section.

Section

This produces a graph showing habitat, velocity or Froude No versus flow for each cross section. The select button is used to select the variable (depth, width, velocity, area, wetted perimeter, Froude No, pool, run, riffles%) that is displayed.

This graph is useful for showing the variation of habitat/flow relationships with habitat type. Usually the shape will differ between runs, riffles and pools, but each habitat type will have a similar shape.

Show as text produces tables of this information for each cross-section and modeled flow.

Reach

This produces a graph showing habitat, velocity or Froude No versus flow for the reach. The select button is used to select the variable (depth, width, velocity, area, wetted perimeter, Froude No, pool, run, riffles%) that is displayed.

The select button is used to select the variable (depth, width, velocity, area, wetted perimeter, Froude No, pool, run, riffles%) that is displayed. Single variables or any combinations can be selected and shown on the graph. Habitat can be shown either as AWS or CSI (reach averaged habitat suitability index).

Error bars can be displayed using Edit/Display>>Graph options when using habitat mapping. The error bars are calculated using bootstrapping with random selection within each habitat type. The error bars are also calculated for the gradient of the graph to try and show how certain you can be of the location of the maximum value and breakpoints.

Show as text produces tables of this information at each modeled flow for the reach and can be copied into excel.

3.5.5 VDF sensitivity analysis

The prediction of velocity distribution is one of the weak points of habitat modeling and a sensitivity analysis is one way of examining the potential effect of errors in velocity distribution on habitat/flow relationships.

The menu item produces a graph of habitat versus flow using three VDF assumptions.

1. Applying the VDFs
2. Not applying VDFs (conveyance assumption with VDF of 1), and
3. A best guess where the assumption is gradually changed from 1 to 2 as flows increase above the survey flow. This assumes that increasing flow will create a more uniform distribution of flow.

The effect of different VDF assumptions of velocity distribution can be examined with Hydraulic calibration>>Velocity pattern. When the distribution of velocity is displayed, Shift F1 will toggle between VDFs applied and best VDFs, Shift F2 will toggle between VDFs applied and VDFs not applied.

3.5.6 Flow fluctuations

This produces a graph that shows how habitat reduces as the amount of flow fluctuation increases. The left axis is the area weighted suitability (AWS) and the bottom axis is the proportion of flow fluctuation.

Flow fluctuations are modeled about a base flow. The base flow is considered to be the normal flow and the fluctuation causes the flow to fall below normal and to increase above normal. It is possible to set the minimum flow the same as the base flow, in which case the evaluation is for fluctuations above the base flow.

The number of modeled steps between the base flow and minimum and maximum flows is specified. For example, if the base flow is 10, the minimum 6 and the maximum 20 with 2 steps, the flows modeled will be 6, 8, 10, 15, 20, where a fluctuation of 6 to 20 is 100% of maximum flow fluctuation and variation from 8 to 15 if 50% of maximum flow fluctuation.

The Select button is used to select the habitat suitability curve for which the results are displayed.

F4 will toggle the display so the bottom axis is flow rather than proportion of maximum flow fluctuation.

3.5.7 Passage width

This produces a graph of reach passage width (using limiting depth and velocity criteria) versus flow. The total width meeting the passage criteria and maximum contiguous width are shown. Show as text also displays the wetted width and the wetted width at the section with minimum contiguous passage.

3.5.8 Standard setting

Habitat Retention

Habitat retention is often used to set minimum flows. For example, retention of 90-100% of habitat at the index flow provides a degree of protection applicable where the species or instream use is highly valued, whereas 60-70% habitat retention might be a standard applicable to a less valued species or instream use. The index flow is typically the mean annual low flow (the minimum flow that occurs every 2 years or so).

This analysis determines flows that provide standards of protection (habitat retention) as a percentage of the habitat (AWS) provided by an index flow, typically the mean annual low flow.

The analysis also calculates AWS up to the maximum flow (specified by user) and determines the flow that provides maximum habitat (AWS).

Tennant method

Tennant considered that width, depth, and velocity were physical instream flow parameters vital to the well-being of aquatic organisms and their habitat.

Tennant studied 10 streams in the US (mostly in Montana and Wyoming) and determined the % of mean flow that would maintain those streams in states of well-being varying from degraded to excellent.

SEFA calculates the mean flow from the imported flow record and presents Tennant's recommended flow regimens.

Tennant Method	Percentage of Mean Annual Flow	
Description	**Winter Season (e.g. October-March)**	**Summer Season (e.g. April-September)**
Optimum range	60-100	60-100
Outstanding	40	60

Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	<10	<10

Tennant also believed that 10% of the mean flow is a minimum short-term survival flow at best and that this was associated with a wetted width of 60% of mean flow width, an average depth of 1 foot, and an average velocity of 0.75 fps.

He considered that average depths from 1.5 to 2 feet, and average velocities from 1.5 to 2 fps were in the good to optimum range.

The problem with the Tennant (or Montana) method is the percentages of mean flow and the resulting depths, velocities and widths will only apply to rivers that are similar to his group of 10 study streams.

The Hydraulic habitat>>Standard setting>>Tennant analysis in SEFA can be used with river survey data to determine the variation in depth, velocity and width with flow and to determine the flows that meet Tennant's standards of well-being for depth, velocity and width.

Tennant's standards for well-being for depth, velocity and width:

Sustain short-term survival	Depth >= 1 foot, velocity >= 0.75 fps, wetted width of 60%
Good survival	Depth >= 1.5 feet, velocity >= 1.5 fps, wetted width 75%
Excellent to outstanding	Depth >= 2 feet, velocity >= 2 fps, wetted width 90%

The Hydraulic habitat>>Standard setting>>Tennant analysis shows Tennant's standards of well-being (short-term survival, good survival and excellent survival) on a graph of depth, velocity and % width at mean flow versus % of mean flow. The text output also lists depth, velocity and % width at mean flow for flows of 10-100% of mean flow.

3.6 SEDIMENT MENU

3.6.1 Flushing flows

This produces a graph of the area of stream bed flushed (deep, and surface) versus flow, using Milhous flushing criteria. Velocity, shear velocity, dimensionless shear stress, suspended sediment size and bed load size can also be displayed using the select button.

The method of calculating shear stresses can be either from friction factor and velocity or from slope and hydraulic radius. The slope can be either surveyed slopes at each cross-section or the average reach slope. The latter is the default because it is most appropriate for high flow modeling when the survey is made at relatively low flows.

The Gessler method is implemented as an alternative to Milhous and this predicts the area flushed of 0.01, 0.1 and 2 mm particles and % armour disturbed.

Flushing flow analysis is used to determine the area of the river bed that a flow will clean of fine sediment and algae.

3.6.2 Deposition

This shows a graph of the % area of the river in which silt or sand will deposit versus river flow. The calculation is based on Shields curve for initiation of movement (i.e., movement/deposition occurs when dimensionless shear stress is 0.056.

3.6.3 Suspended

This produces a graph showing how suspended sediment concentration will decrease with distance downstream, assuming no input of sediment. This models the settling process of fine particles (sticky river bed) in water following Einstein's (1968) work on siltation of redds. The calibration (size of particles etc.) should be based on field measurements of sediment concentration versus distance downstream.

3.7 TEMPERATURE MENU

Two methods are used to calculate water temperatures. A Lagrangian model based on the model described by Rutherford et al. (1997[2]) and the Theurer model. The heat basics of the Lagrangian model are the same as in Theurer's model but the solution method is different particularly for estimates of daily maxima and minima. There is good agreement between the Lagrangian model and Theurer's model for daily mean temperature predictions.

Set Time Zone and Location

Water temperature and dissolved oxygen models calculate sunrise and sunset times and day length using the geographic location of the reach. The results of this calculation are shown for "today's" date. However, when used for temperature or DO calculation the times and day length are calculated for the dates specified for the temperature or DO model.

Calibrate/Run reach temperature series

Calibrate/Run reach temperature series enables the import of a time series of climate, flow, and water temperature data. Shade, wind, and bed conductivity can then be adjusted to calibrate the model for the Lagrangian and Theurer models. Maximum temperature predictions can also be compared to measured maximum temperatures, and this may show a difference in the ability of the two models to predict daily maximum temperature.

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[2] Rutherford, J. C.; Blackett, S.; Blackett, C.; Saito, L.; Davies-Colley, R. J. 1997. Predicting the effects of shade on water temperature in small streams. New Zealand Journal of Marine and Freshwater Research 31: 707-721.

The time series model can be run with different flows series by including the modified flow series in the dataset that is imported. First fit the model with the measured flows, and then rerun the model (with fitted parameters) for the modified flows.

Reach Model

Modeling the effects of flow on water temperature can also be carried out using the Temperature>>Reach model menu. Flows and climate data are entered and the variation of maximum, minimum and daily mean water temperature with distance downstream is shown as a graph.

Water temperature predictions using Theurer's model can be displayed by selecting the Theurer model in Edit/Display>>Graph options. This option does not allow the inclusion of tributaries.

The initial assumptions are equilibrium conditions so that there is no variation in water temperature. Non-equilibrium assumptions are set with the advanced button at the bottom of the window.

Lateral or tributary flows can be allowed for in the advanced dialog, except if Theurer's model is used.

Network model

This has not yet been implemented.

3.8 DISSOLVED OXYGEN MENU

3.8.1 Set Time Zone and Location

Water temperature and dissolved oxygen models calculate sunrise and sunset times and day length using the geographic location of the reach. The results of this calculation are shown for "today's" date. However, when used for temperature or DO calculation the times and day length are calculated for the dates specified for the temperature or DO model.

3.8.2 Reach

The variation in dissolved oxygen concentration (mean daily and minimum) is calculated and displayed for the specified flow range. The reach (single station) DO model applies to streams with a reasonably homogenous distribution of aquatic plants (which can include algae) in a reach.

3.8.3 Network

The network (multiple station) procedure calculates dissolved oxygen concentration and biological oxygen demand (BOD) along a river and can include inflows from tributaries, point source discharges and outflows (abstractions).

Six processes are modeled to calculate DO along the river. These are tributary inflows (flow, DO and BOD), outflows (abstractions), longitudinal advection (downstream transport by the water current), longitudinal dispersion (the way in which DO and other constituents of the water spreads out longitudinally as they flow downstream), re-aeration (interchange of oxygen between water and atmosphere), and aerobic bacterial decomposition.

3.8.4 Dilution

This has not yet been implemented.

3.9 TIME SERIES MENU

3.9.1 Import Flow Series

An import wizard is used to import a text or EXCEL file containing date and flows. A wide variety of date formats are recognized. Date can be in either dd/mm/yy or mm/dd/yy order.

The flow series needs a header line for the column headings. This line must be immediately before the data. The wizard allows lines before the header to be ignored. It also allows comment lines to be ignored.

3.9.2 View Flow Series

This produces a graph of one or more flows versus time. Edit/Display>>Graph Options can be used to alter the display.

3.9.3 Seasonal flow Statistics

Seasonal flow statistics for mean, median, minimum, maximum, 25% and 75%, and standard deviation are shown on a bar and whiskers graph and produced in a table. Any definition of seasons can be specified. No interpolation is carried out and values are the means etc. of all values in the time period. For example, if there were only 2 values specified in a month, the statistics for that month will be the mean, median etc. of those two values.

Incomplete years or months are not marked, but the user can see whether the correct number of values are in each season by displaying the sample size.

3.9.4 Indicators of Hydrologic Alteration

The indicators of hydrologic alteration are a set of hydrological statistics and indices, largely based on a paper by Poff (1996).

The calculation of IHA uses the imported flow series. The flows should be daily mean flows where the flow is the daily mean flow for the date specified in the imported file. If there are gaps in the flow record, they are filled by linear interpolation unless the option for no interpolation is checked. Flow data are not extrapolated so that the first and last years may be incomplete.

Flow statistics are calculated for calendar months and years. For example, February mean flows in a leap year will be the arithmetic average of 29 values. Annual flow statistics are based on the year of data and moving means do not overlap into preceding or following years.

Most statistics are self-explanatory, but some may be unfamiliar to users.

Zero days is the number of days with zero flow.

The base flow index is the annual 7-day minimum flow divided by the mean annual flow

The median rates of rise and fall are medians of all positive or negative changes in flow. Zero flow changes are ignored.

A reversal occurs when the flow on a day is less than the previous day and less than the next day or when the flow on a day is greater than the previous day and greater than the next day

The coefficient of variation is the standard deviation divided by the mean flow.

The coefficient of dispersion is the difference between the 75 and 25 percentiles divided by the median flow.

High flows are flows that exceed the 75 percentile. Low flows are flows less than or equal to the median (50 percentile). Flows between 50 and 75 percentiles are considered as recession. A high event begins when the flow exceeds the 75 percentile or when the flow is in the recession range and the flow increase is greater than 25% (i.e., (Q2-Q1)/Q1 > 0.25). A high flow event ends when the flow falls below the median flow or when the flow is in the recession range and the rate of flow decrease is less than 10% (i.e., Q1-Q2)/Q1 < 0.10. A low flow event begins when the flow falls below the median flow.

The average length of an event is the total number of days of high or low flow divided by the number of events.

3.9.5 Riparian inundation analysis

This analysis requires a river model with good high stage stage-discharge curves and a flow series. Inundation heights and areas are calculated as a height above some base flow. The frequency, timing and duration of inundation is calculated for a specified height above base flow.

3.9.6 Select AWS/Flow Relationship

The first dialogue displays a list of the AWS/Flow relationships that were last calculated for the open rhbx file. If no file has been opened, or no AWS/Flow relationships have been saved in the open file, a blank second dialogue will be displayed. If you press the Import from File button, you can either import an AWS/Flow relationship from a SEFA file or a text (csv, xls*) file. If the first dialogue displays the AWS/Flow relationships that have been saved in the open SEFA, and you wish to use other relationships, press the Cancel button and a blank second dialogue will be displayed, allowing you to import relationships from another file.

Any of the listed relationships can be selected and saved. When selected the values will be shown in the table and a graph of the relationship is displayed. When the relationship is saved (after setting methods of extrapolation), the graph, table and selection box is cleared and the saved relationship is shown in the saved list. Relationships that have been saved can be deleted by selecting them in the saved list and pressing the delete button.

Extrapolation above and below the maximum and minimum flows in the AWS relationship can be set as the flow value at which AWS becomes zero. For low flows, the AWS at zero flow can be specified and for high flows, a constant value (last value in the relationship) can be used. The default extrapolation is that the flow values for zero AWS are calculated by linear extrapolation of the first two pairs of values and the last three pairs of values. If the extrapolation of the last three values does not intercept the flow axis, constant extrapolation is assumed. If the slope of the first two values is negative, the extrapolation is vertically down. If the slope is positive then the intercept with the flow or AWS axis is used as the extrapolated point.

Any AWS/Flow relationship, either an existing SEFA file in which the relationship(s) have been saved or a text file with pairs of flow and AWS values and width as text (see Import AWS/Flow relationship as Text), can be imported by clicking the Import from file button.

Text file data format

The data should follow a line giving a column name for the relationship in the first column. Column names for the other columns are optional. The columns can be separated by blanks, tabs, or commas.

Data should be in a row by column matrix with each row containing a pair of flow, AWS and wetted width values. The flow should be in the first column, the AWS value in the second and the width in the third.

SEFA can read comma delimited files "*.CSV", text files with blanks between data values "*.TXT, *.DAT, or Excel files "*.XLS" or "XLSX".

If an Excel file is opened, a list of worksheets is displayed and any one can be selected.

When the file is imported, it is listed in the available relationships along with any relationships that have previously been calculated for the rhbx file.

When an available relationship is selected, the values are listed and the relationship is shown graphically.

Example:

Common bully - flow m3/s and AWS m2/m and width (m)	AWS (m2/m)	Width (m)
0	0.806	2.50
1	9.915	5.50
2	9.169	6.19
3	7.966	6.67

	4	6.833	7.05
	5	5.734	7.36
Brown trout (< 100 mm)			
	0	0	2.50
	1	7.497	5.50
	2	7.94	6.19
	3	7.582	6.67
	4	6.433	7.05
	5	5.266	7.36
	6	4.46	7.64
	7	3.807	7.88
	8	3.198	8.10
	9	2.678	8.30

3.9.7 View AWS series

The imported flow series are converted into area weighted suitability values using the selected AWS/Flow relationship to produce a graph of AWS versus time. Edit/Display>>Graph Options can be used to alter the display.

3.9.8 AWS Duration Analysis

The imported flow series are converted into area weighted suitability values using the selected AWS/Flow relationship. These data are analyzed to determination the exceedence statistics (i.e., the % of time that the AWS value is exceeded. There is no interpolation or extrapolation of the flow series, so that AWS statistics are based solely on the values in the imported flow series file and the AWS/Flow relationship. The text output also lists the mean, median, minimum, maximum, and standard deviation values of AWS in the series.

3.9.9 Seasonal AWS Analysis

The imported flow series are converted into area weighted suitability values using the selected AWS/Flow relationship. Seasonal flow statistics for mean, median, minimum, maximum, 25% and 75%, and standard deviation area weighted suitability are shown on a bar and whiskers graph and produced in a table. Any definition of seasons can be specified. No interpolation is carried out and values are the means etc. of all values in the flow series time period. For example, if there were only 2 values specified in a month, the statistics for that month will be the mean, median, etc. of those two values.

Incomplete years or months are not marked, but the user can see whether the correct number of values are in each season by displaying the sample size.

3.9.10 UCUT analysis

This analysis uses a daily mean flow series and a relationship between flow, AWS and width to calculate the percentage of time in a bio-period (e.g. spawning season) that the AWS is continuously below a specified level (the thresholdl) in the bio-period for durations of 1 to the length of the bio-period.

3.9.11 Event Analysis

Event analysis presents a year by year and season by season analysis of events, such as high and flow occurrences.

Two types of event can be analyzed.

1. Number of recorded instances (e.g., days that meet the event criteria)
2. Number of separate events (e.g., where the event criteria are met contiguously throughout the event).

4 Field Survey Techniques

The purpose of a hydraulic habitat survey is to calculate water velocities and depths for a range of flows, and compare these with preferred instream conditions and their co-occurrence with stationary stream elements (e.g., substrate, bank formations, and cover).

Usually, a survey aims to provide information on conditions over a range of flows.

Hydraulic habitat surveys may also be used to determine the effect of flow on spawning grounds or fish passage. Surveys of this nature usually concentrate on known spawning areas or shallow rivers sections.

The habitat types in the section of river to be surveyed are determined by examining a reasonable length of river. The habitat types, pool/run/riffle, can sub-divided depending on the river and survey purpose. Once the habitat types are defined, the length of each is measured and cross-sections randomly selected in each habitat type. Often, the first cross-section is chosen in the least common habitat type, with other cross-sections located in adjacent habitat types.

Cross-sections should be clearly identified in the field and field data (offset distances, depths, number of revolutions and times and especially levels) should be accurate and systematically recorded.

A tagline or tape is strung across the river, usually at right angles to the flow. It does not matter whether the tape zero is on the left or right bank, but it is preferable to be consistent, so that when plotted data are viewed, cross-sections will be consistently either looking upstream or downstream.

Cross-sections are located within a section of river so that they represent the range of conditions that occur. There are two ways of doing this.

4.1 Reach location

4.1.1 Representative

The reach or section of river surveyed should represent the average characteristics of the river and contain a range of habitat types or attributes.

A representative reach should contain one or two pool/run/riffle sequences that are considered representative of a longer section of the river. The distance between cross-sections through a representative reach is usually small, especially in transition zones between habitat types.

The distance between cross-sections is used to calculate the percentage of reach (habitat weight) it represents. If percentage values are specified in the input file, these are used instead of the percentage calculated from reach distances.

The sum of the habitat weights should normally sum to 1 (100%). If they do not sum to 1, a warning is issued and the user can choose to either correct the weights or use the data with weights that do not sum to 1.

If the number of cross-sections in a reach is small, results can be unduly influenced by unusual cross-sections.

4.1.2 Habitat mapping

The reach is made up of cross-sections randomly selected from each of the habitat types present in the river. Technically this is known as stratified random selection.

Mapping of a section of the river is carried out to define the habitat types present and to determine the percentage of each type within the reach. Each cross-section represents the percentage of the habitat type in the reach divided by the number of sections in that habitat type.

For example, if riffles made up 25% of a section of river and 6 cross-sections were surveyed in riffles then each cross-section would represent 25/6 or 4.2% of the river section.

The sum of the habitat weights should normally sum to 1 (100%). If they do not sum to 1, a warning is issued and the user can choose to either correct the weights or use the data with weights that do not sum to 1.

4.1.3 Multiple reaches

A number of reaches may be surveyed to represent the different characters of sections of stream. These reaches can be summed to give an average for the river. Usually, a river will only be divided into multiple reaches if the flow varies between reaches. For example, upstream and downstream of a tributary stream.

When characteristics of a multiple reaches are summed, each cross-section is weighted by the habitat weight and the total reach weight is the sum of the cross-section weights. With multiple reaches, the sum habitat weights for each reach need not sum to 100% and the weights can be used to weight reaches according to the length of river they represent. For example, if the survey was of two reaches upstream and downstream of a tributary. The reach upstream of the tributary might represent 40% of the length of river and the downstream reach might represent 60%. The sum of the habitat weights for the upstream reach would sum to 0.4 and the sum of the downstream reach weights would sum to 0.6. When the two reaches are analyzed together, the proportion of the reach modeled will be given as 100%.

If the habitat weights of two reaches each sum to 100%, each reach will be given equal weight and the proportion of the reach modeled will be given as 200%.

4.1.4 Fish passage

Reach surveys, either habitat mapped or representative, are usually carried out to determine average conditions and may not include the shallowest or swiftest sections that are critical for fish passage.

If fish passage is to evaluated, the surveyed cross-sections should include potential passage barriers, for example, the shallowest riffles. The reach can then be modeled to determine the flow at which the depth falls below a critical level for the passage of fish.

4.1.5 Number of cross-sections

The number of cross-sections surveyed and the total number of measurements across each section should increase as the variability of the stream geometry increases.

The number of cross-sections required for a comparison of habitat quality between sections of river or between rivers is greater than the number required to establish the pattern of habitat variation with flow.

4.2 Data collection

The input data usually consist of offset, depth and velocity data collected during the *survey* (sometimes there may be additional surveys of the same reach at other flows), and stage-discharge calibration data collected at a number of *calibration visits* (recommended minimum of two), It is possible to collect *calibration* data before the survey is done.

4.2.1 Data collection during the *survey*

During the *survey*, a number of cross-sections (sometimes referred to as 'sections' in SEFA) are entered into a reach. Two approaches can be used for the representation of cross-sections; habitat mapping and representative reach.

In the habitat mapping approach, the reach under consideration is mapped according to the habitat type (run, riffle, pool), and each cross-section is given a percentage weight according to the proportion of the reach that it represents. This mapping is carried out by walking along or in the river and measuring the coverage of each habitat type. The distances between the cross-sections need not be measured, and only the percentage weights are used in the calculation of AWS. For example, if data were collected at 15 cross-sections, they could be five 5 cross-sections placed in runs, 5 in riffles and 5 in pools. The sum of the habitat weights should normally sum to 1 (100%). If they do not sum to 1, a warning is issued and the user can choose to either correct the weights or use the data with weights that do not sum to 1.

In the representative reach approach, data are collected over a relatively short length of river (e.g., 150 to 500 m). The reach is chosen to represent the longer river sector that contains it. The cross-sections are placed where longitudinal changes in water surface elevation and cross-section occur. Distances between cross-sections are measured (an isometric view would picture the cross-sections with the correct spacing), and all elevation data are surveyed to a common level. This is more time-consuming but allows greater checking of water level data. Usually, the cross-section weight is calculated from the section distances. However, it possible to enter any set of weights (that should usually sum to 1). This allows the cross-sections within a representative reach to be weighted according to habitat mapping carried out over a longer river sector.

In addition to the mapping (for habitat mapping) or measurements of the distances between cross-sections (for representative reach), the survey includes:

(a) The flow is gauged at all cross-sections. This includes measuring the offset, the depth and the average vertical velocity at a number of points across the stream.

(b) The points in the cross-section above the water level (on the banks) are surveyed to allow modeling of the water surface at levels above the current water level.

(c) The % composition of substrate size categories are recorded in an area around each point in the cross-section, or alternatively a substrate index could be assigned.

(d) Temporary staff gauges are established near the banks at all cross-sections, and the water levels are measured. If the representative reach approach is used, the water levels are surveyed to a common level.

(e) The stage of zero flow (SZF) is identified and leveled for all cross-sections.

The SZF is the water level that would be at the cross-section if the flow were zero. The SZF is the higher of the two levels: (1) the cross-section minimum, (2) the highest point on the thalweg downstream from the cross-section. A pool usually has a downstream control, and (2) is the SZF; a riffle has no effective downstream control, and (1) is the SZF; a run may or may not have a downstream control that would retain water in the run if the flow were zero. In some high flow situations, the SZF (as it is used in the rating curve equation) may not relate to either the minimum cross-section level or the level of the downstream control and is taken as the constant that produces the best fit to a set of stage/discharge measurements.

4.2.2 Rating calibration visits

Rating curves (also called stage-discharge relationships) are used to convert flow (Q) into water level (H), and thus depth. Two or more rating calibration visits are required to establish the variation of water level with flow.

Stage/discharge calibration should be done as soon as possible to minimize the chance of rating changes occurring between the survey and rating calibration measurements.

On the rating calibration visit, flow is measured at a good gauging site and the water level at each cross-section (or downstream section for WSP analysis) measured. Bench marks and temporary gauge levels should be checked against the original survey in the field and the source of any discrepancy determined, as this could be either survey error or benchmark movement.

At each calibration visit, the data collection includes:

(a) a flow measurement at one (the most suitable) cross-section, and
(b) the water level at all cross-sections relative to the temporary staff gauges. If the representative reach approach is used, the water levels are surveyed to a common datum level.

4.2.3 Survey flow

The survey flow is the best estimate of the flow during the *survey*, i.e., when the cross-section data are collected.

The menu Edit/Display>>Flows shows the calculated flow and other hydraulic parameters at each cross-section. The flow at each cross-section is calculated assuming that the velocity of velocities measured at each point are mean velocities in the vertical. Usually, single velocity measurements will be at 0.6 times the depth. If velocities follow the “normal” logarithmic velocity profile, the average velocity is found at around 0.6 times the depth below the water surface, or as the average of the velocity measurements if more than one velocity was measured in the vertical (e.g., in 0.2 and 0.8 times the depth below the surface, or in 0.2, 0.6 and 0.8 times the depth below the surface). Because of errors related to measurements and integration of velocities, the calculated flow for each cross-section usually varies up to 5-10% from the average, and sometimes more, especially for riffles and pools.

If data for all cross-sections were collected at the same time and there was no water loss or gain between cross-sections, then the same survey flow will apply to all cross-sections. SEFA uses the average as the default value for the survey flow; however, another value can be specified under 'Set survey flow'. In other situations, the user may want to average the flows from suitable run cross-sections and not use the values calculated from riffles and pools.

Note that at the rating calibration visits, there is often only one flow measurement (made very carefully with sufficient measurements of velocity and depth to produce an accurate flow measurement), so there is no choice.

4.2.4 Cross-section measurements
4.2.5 Offset origin

The offset is the distance across the cross-section from an origin. Usually the origin is the zero of the tape or tagline, but negative values can be used if required.

Measurements are made along each cross-section, usually at fixed intervals, but with additional measurements at the water's edge and abrupt changes in section. Changes in grade across the section should be recorded to obtain the best representation of the section area.

4.2.6 Bank measurements

Offset distances, heights above water level, and substrate composition or substrate index are estimated for the bank and water’s edge at all changes of grade, usually up to about 0.5 m above water level or up to the water level of the highest flow to be simulated.

Heights above water level (a negative value of water depth) can be estimated or measured down from a horizontal tagline using wading rods or by leveling.

4.2.7 Instream measurements

An initial estimate of offset spacing can made by dividing the river width by 10-15, and rounding down to the nearest convenient increment.

Measurements are made at regular intervals across the stream, with extra measurements where the depth or velocity changes suddenly. This means that boulders, as well as overall bed shape, should be well defined by measurements taken at the foot, water's edge, and top of large boulders or similar bed elements, on both the left and right sides.

Each water edge should be a measurement point with zero depth and velocity. This makes sure that there is no confusion between points measured above the water level and those measured below, such as would occur if the negative sign for a point above water level were inadvertently omitted.

After the last instream measurement, the outer water edge and bank is defined.

Velocity measurements

Velocity measurements should be made at all instream offset points and very small velocities should not be ignored. Reverse currents should be recorded as a negative number of revolutions.

The movement of silt can be used to assess current direction and magnitude when velocities are too small to measure. Velocity or revolutions and time measurements (at 0.6 depth below water surface or at 0.2 and 0.8 if the depth exceeds 1 m or there is an unusual vertical velocity distribution) are recorded.

Water velocities can be measured with 20-second counts rather than the more standard 40 second count. If this is done, the actual count and time should be recorded rather than doubling a 20 second count to make it appear as a 40 count.

Attributes

Attributes (substrate etc.) are recorded for every offset both instream and on bank. Generally, visual assessments are the only practical method of assessing substrate composition. The average substrate composition in the region of the measurement point should be assessed. The area examined will depend on offset spacing (i.e. half way to adjacent offsets), but should not exceed 0.5 m either side of the point and 1 m upstream and downstream.

Substrate categories used are commonly, bedrock, boulder (>264 mm), cobble (64-264 mm), gravel (8-64 mm), fine gravel (2-8 mm), sand (<2 mm), silt, and vegetation (bank or instream debris). The advantage of specifying substrate composition in these size classes is that particle sizes can be calculated for sediment modeling. However, the categories are arbitrary and any subdivision is possible and could be changed depending on the purpose of the survey.

The categories used in the survey should match those described in the habitat suitability curves. Substrate habitat suitability is calculated from the substrate categories. The substrate habitat suitability curve describes the suitability of each substrate category, and the substrate suitability at measurement point is the sum of the suitability for each category multiplied by the percentage of that substrate category at the point.

For example:

A spawning suitability survey might only use two substrate categories, suitable for spawning and unsuitable. The suitable category could be called "Gravel" and the unsuitable category "Vegetation". The habitat suitability curves would give "Gravel", substrate index 5, a weight of 1 and all other substrate categories a weight of 0.

Alternatively, a substrate index could be assigned to each measurement point. The name of the substrate index (e.g., INDEX) is specified as an attribute and should not conflict with substrate category names. The habitat suitability curve for the substrate index should have the same name as the attribute and should not conflict with the reserved names of DEPTH, VELOCITY and SUBSTRATE.

4.2.8 Measurement of water level

Temporary staff gauge

The most accurate method of measuring water level is to establish a temporary staff gauge in the river. The water level can then be measured from the top of this gauge. Reinforcing bars about 50 cm long or wooden stakes about 1 m long are ideal for this.

This is driven into the streambed in a sheltered location on the cross-section in about 10-20 cm of water. The top of this gauge can be used as one of the section benchmarks. Two other benchmarks should be established on the bank so that any movement in the temporary gauge can be detected and corrected if necessary. Each benchmark should be leveled and the water level referenced to the top of the gauge (zero if flush with the water surface). A gauge can accurately measure small changes in water level for derivation of the cross-section rating curve.

The purpose of water level measurements is to establish the change in water level with flow, so pins should be located where turbulence is minimal and levels can be measured accurately. The water level at the gauge need not be the average water level across the section, but must reflect changes in the average level. For WSP modeling, the water level must represent the average water level of the cross-section.

If bars are driven flush with the water surface at the survey flow, it is only necessary to measure the height above or below the top of the pin to determine the change in water level on subsequent visits.

If pins or gauges are to be left for some time, they should be leveled into two benchmarks on the bank so that any movement can be detected.

Water surface profile water level

For water surface profile modeling, the water level should represent the level of the bulk of the flowing water, and should be measured at three positions across the section - left bank, right bank and at a mid-point. This usually involves leveling with a staff and level. When leveling the water surface at the banks, the staff should be held clear of any instream obstructions which are likely to influence the water level locally.

The longitudinal flow profile is the level at each cross-section plotted against the distance upstream and should be a smooth curve without anomalies such as water flowing uphill.

All leveling should be closed and carefully checked. Errors in leveling water surfaces are difficult to detect retrospectively and there is rarely any opportunity to repeat the measurements.

Braided channels

Each channel in a braided channel is initially treated as a separate cross-section, with temporary staff gauges in each channel. If it is found that the level variation with flow in each braid is similar, the braids can be treated as one continuous cross-section, otherwise they are analyzed separately with survey flows, rating curves, and stages of zero flow varying at each cross-section.

This procedure is repeated until the required number of cross-sections is surveyed. If flows are changing during the survey, stage at one site should be recorded throughout the day so that this can be related to the time and flow of each cross-section survey.

5 River Model Files

SEFA stores data in non-ASCII files with the extension *.rhbx*. This file contains binary information describing the data and calibration model for a reach of a river.

Survey data can be entered directly into the program, or they can be entered into Excel files (extension **.xls** or **.xlsx**) or ASCII files (extension **.txt** or **.hab**) and imported into SEFA and saved in a data file with the extension *.rhbx*. Entering field data into EXCEL and then importing is the recommended method for survey data.

Existing RHYHABSIM rhb or RHABSIM rhb files, PHABSIM DOS text (*.ifg) and PHABSIM windows files (*.phb etc.) can also be imported.

A SEFA file contains the river model file, as well as other components storing the calculation options for that file, the last set of flows used for calculations, and AWS-Flow relationships that have been saved.

The file component “SEFA.RHBX” contains the river model data. The component “preferences.ini” contains the calculation preferences, the component “PRFS.RPF” contains the habitat suitability curves, the component “FLOWS.RPF” contains the flows that have been specified for the last calculation, and the components “AWSFLOWS_date_time” contain the AWS/flow relationships that have been saved.

The components preferences.ini, PRFS.RPF, FLOWS.RPF and AWSFLOWS_date_time can be deleted using Edit/Display>>RHBX File contents, although this should only be required to delete saved AWS/Flow relationships that are no longer required. If preferences.ini is deleted Calculation preferences will be replaced by default values. If PRFS.RPF is deleted, no habitat suitability curves will be associated with the file.

Information (Notes) about each rhbx file can be viewed and edited in the Edit/Display>>RHBX File contents menu.

Temporary files with the suffix “.RPF” are created during the execution of the program. If any such files are present after program execution, they can be deleted.

Warning

When importing an EXCEL file as text, attribute and cross-section names are enclosed in quotes. Microsoft EXCEL uses a single quote to indicate text data and will remove any single quotes when they are the first character in a cell. To get around this behavior you can either use double quotes (") around attribute descriptors or if using single quotes, you must enter two single quotes or alternatively ensure that data items surrounded by single quotes are not the first piece of text in the cell. EXCEL can also change the value you enter when you enter the % sign.

These difficulties can be avoided by encoding as EXCEL csv. This style does not require quotes or % signs but does require every name or value to be in its own cell. It also requires that attribute values be in the same column as their respective attribute name in the reach header and blank values are assumed to be zero values.

5.1 Units

Input and output data units can be in either metres or feet. With input data, decimal points need only be entered where required.

SEFA is basically metric and all internal data storage and computations are metric. Under the menu File->Preferences->Display there is an option to change the display units. This means that output will be converted to feet if your display units are feet.

When the program starts, SEFA looks at the language. If it is English (US), it sets the initial display units to feet, otherwise it is set to metric.

If you import a file with US display units and you don't specify units in the import file then you are asked “Are the units US?”. If the units are feet then answer yes, otherwise if the units are answer no. If the import file units are feet, the numbers in the import file are converted to metric for the internal calculations.

If the display units are metric, you are asked “Are the units metric?”. This means that the numbers in the import file are not converted to metric for the internal calculations.

offset, depth, distance	Metres, feet
elevation or reduced level	Metres, feet
flow	cubic metres/second (m^3/s), cubic feet /second (fps)
velocity	metres/second, feet/second
current meter revolutions	integer number
time for revolutions	seconds
substrate attributes	Percentage (%)
other attributes	any unit
Temperature	Degrees C
Dissolved oxygen	mg/m^3

5.2 River Model Direct Data Entry or Edit (Edit/View)

Data can be entered directly into a newly created file (New option in the File menu) or an existing file can be opened and edited.

If the data are imported successfully, they are automatically calibrated and the calibration results are saved in the .rhbx file. Changes to the calibration are also saved in the .rhbx file. If import is not successful, the .hab or .xls files can be edited in SEFA and saved in their original formats (.xls, .txt, or .hab) before re-importing. Once a file is calibrated, the data held in the .rhbx file (input data and calibration data) can be exported as a trio of ASCII files: .hab, .vdf and .con, the latter two containing the calibration data (see later). If the .vdf and .con files are present when importing a .hab file, they can be imported with the .hab file.

When you clicked File>>New or have opened a file and clicked 'Edit/Display>>'Edit/View', you will see four tabs: 'Cross-sections', 'Attributes', 'Points' and 'Gaugings' (for representative reach files there is also a 'Layout' tab).

5.2.1 'Cross-section' tab

The 'Cross-sections' tab holds a summary of data from cross-sections, often named according to whether they were placed in a pool, run or riffle. Pools are sections of stream with relatively deep and slow-flowing water, runs have around average water depth, and riffles have water with relatively shallow and fast-flowing water. A drop-down list allows the user to select the habitat type of the cross-section. The choices are listed alphabetically: glide, pocket, pool, other, rapid, riffle, run. This information is presented in the “Reports Summary” in the Hydraulic Habitat menu. Information can be viewed and edited in the Edit/Display>>RHBX File contents menu.

The title comment can store a title (256 characters) for the survey and the comments field can store as much information about the survey as required. A comment (256 characters) can also be stored about each cross-section. This field is on the extreme right of the spreadsheet tabulation of cross-sections.

To the far right on the 'Cross-sections' card you can see which approach has been used ('Habitat mapping' or 'Representative reach').

Where the reach is a 'Habitat mapping' type, the numbers given under 'Distance' are not used for any calculations (and here they were just numbered consecutively), although it is useful to record the location of the cross-section along the river. The '% Reach' data are important in that they indicate the percentage that each cross-section represents of the total reach. For example, if each of the five 'run' cross-sections represents 13.2% of the reach, then 66% of the reach is classified as 'run'. If you change a 'Habitat mapping' reach type to a 'Representative reach' type, the '% Reach' values will be recalculated (see how below), and the previous values can be restored by simply changing back to a 'Habitat mapping' reach type.

For representative reach files, the distances between cross-sections are important because they are used to calculate the proportion of the reach that each cross-section represents. Try for example open Opuha.rhb to see that the '%Reach' area is calculated from the cross-section distances. The 'length' of each cross-section is taken as the distance between the halfway points to the neighboring cross-sections (see also the fifth card 'Layout'. Note: If distances are altered in the layout they apply only to the graphic displays of the reach and are not used in the calculation of AWS). Because the first and last cross-sections only have one adjacent cross-section, their lengths are twice half the distance to that cross-section. The total reach length is the sum of the individual reach lengths. This is the distance between the first and last cross-sections plus half the distance between the first pair plus half the distance between the last pair of cross-sections. The '%Reach' represented by each cross-section is then its length divided by the sum of all the cross-section lengths. You can adjust the layout to give a more realistic plan view of the reach, see 'Model', 'Plan view' (this only works for representative reach files).

The fourth column on the 'Cross-sections' menu gives the water level for each cross-section as read on the temporary staff gauge. If levels of points in the cross-section are given relative to the water level, then the water levels are used to convert the measurements into a common datum. For example, if the water level at the time of survey is 9.8 m above sea level, a measured water depth of 0.32 m will correspond to a level of 9.8 m – 0.32 m (9.48 m above sea level).

Four columns are provided to record the exact cross-section locations. Each cross-section location can be identified by the coordinates of the zero offset (X zero coordinate, The X coordinate will normally be east (across the page) and the Y coordinate north (up the page). If location data are recorded in these columns, you will be asked whether they should be used to generate the necessary data for the reach layout.

5.2.2 Cross-section water level

This is the water level at which measurements of water depth and velocity are made. The water level is referenced to an arbitrary datum and need not be referenced to the same datum.

This water level and the flow that is calculated from measured depths and velocities make up the survey stage and measured flow.

The water level at the time of the survey is used to convert measurements of water depth to a common datum. Levels in terms of a common datum are termed reduced levels or elevations. Data taken from maps or topographic surveys are usually already in terms of reduced level or elevation.

For habitat mapping, a consecutive number can be specified as a distance rather than the actual distance between cross-sections. If any two consecutive cross-sections have the same distance, they will be regarded as multiple channels of one transect.

For habitat mapping, all water levels do not have to be to the same datum. Each cross-section can use its own local datum, usually the top of the peg or pin marking the location of the cross-section.

Each braid or multiple channel is treated independently, and has their own set of levels, survey flows, and datum.

5.2.3 'Attributes' tab

'Attributes' define the substrate categories (or any other attribute) that were registered in the cross-section. The names of these attributes are also shown under 'Points', along with other cross-section data.

An attribute is any characteristic of a point on a cross-section. Attributes are most commonly used to describe substrate composition (% of each type).

Eight standard substrate categories are listed as the available attributes. However, an attribute with any name, such as INDEX for a substrate index, can be added to this list.

Attribute specifications can be added or deleted by first clicking on the list of attributes (blank if none have been entered). Once in this list, attributes can be added, either by selecting one of 8 substrate categories or entering a name. Any name can be edited or associated with a different substrate category.

When a new attribute is selected for a reach, zero values are generated for each point in each cross-section. If an existing attribute is removed, all values for this attribute are deleted.

The maximum number of attributes for a reach is 10.

Reserved Substrate Names

There are eight basic substrate categories:

Id.	Substrate	Size (mm)
1	Vegetation	-
2	Silt (Mud)	<0.06
3	Sand	0.06-2
4	Fine gravel	2-8
5	Gravel	8-64
6	Cobble	64-264
7	Boulder	>264
8	Bedrock (Rock)	-

If any of the substrate categories are specified, the Check menu option will check that the substrate composition at each point sums to 100%.

If the substrate composition at a point does not sum to 100%, the error can be corrected in the Edit/View option of the Edit/Display menu.

It is possible to get an error message stating that the substrate composition does not sum to 100%, but the Check option indicates that the substrate composition at all points is 100%.

This situation arises when two attributes have been assigned to the same substrate category, usually there will be an 'S' and 'M' attribute with both assigned to mud. To correct this, edit the data (Edit/View option of Data) and go to the attribute page. Click on the offending attribute (usually S) then the edit button. Assign it to the correct substrate category (e.g., sand), close window, saving the file.

5.2.4 'Points' tab

These data include calibration formula for the current meter, as well as coordinates for the points in the cross-section (offset and level), velocity (or revolutions and time) at 0.6 (or 0.2 and 0.8) times the depth below the surface (for points in water), and substrate composition at each offset. Scroll between the cross-sections by using the arrows.

The Points card contains:

Name - any name

Percentage reach (for Habitat mapping)

Distance (for Representative reach)

Water level - water level at time of survey

Points can be added, deleted or inserted by first clicking on the Point number at the left of the row. A comment can be added to any point value

A distance or section ID is specified for each cross-section. The distance and section name identify the location of the cross-section.

The section name usually identifies the habitat type and location.

The percentage is the percentage of the reach represented by the cross-section. In a representative reach, this percentage is the percentage of the reach length. With habitat mapping, each cross-section represents a percentage of the habitat type.

Attributes are shown under 'Points', along with other cross-section data. 'Attributes' define the substrate categories (or any other attribute) that were registered in the cross-section.

Cross-section data must specify offset and depth pairs. The depth can be in terms of reduced level or more commonly as a depth, where the depth is the height above (-ve) or below (+ve) the water level.

If only depth and offset are specified in a cross-section, the flow is assumed to be the survey flow and velocities are calculated assuming a uniform flow distribution (i.e. VDF=1).

If velocities are entered, they can be pairs of meter revolution counts and time or a velocity. If the former, the meter calibration constants must be specified.

The cross-section form lists:

- distance
- name
- water level

and optionally

- current meter calibration constants (Levels only not checked)
- percentage of reach (Habitat mapping)

Most of these items can be entered/altered on either this card or on the Cross-section card.

Checking the Velocity checkbox will set up the form for entry of velocities rather than revolutions and times.

New points can be added to the cross-section by either pressing enter after the last point is entered or by clicking the Add button when the whole row is selected. Points can also be inserted or deleted within a cross-section. Click on left of row to select the whole row.

A new cross-section can be added with either the add or insert button on the Cross-section card.

5.2.5 Meter constants

The meter constants are the slope and constant in the equation used to convert the measurement of revolutions/second to a velocity, i.e.

velocity = slope x revolutions/second + constant

Multipoint velocity measurements

Multi-point velocity measurements (e.g. at 0.2 and 0.8 or 0.2, 0.6 and 0.8 depth) are averaged to give the mean velocity in the vertical.

Multipoint measurements repeat the offset and depth measurement with the velocity reading or count at each point in the vertical. The order (0.2 or 0.8) does not matter. Multipoint velocity measurements must specify exactly the same offset and depth. Two sets of measurements with the same offset and different depths will be assumed to be a vertical wall.

5.2.6 Offset and level

The offset is the distance from the cross-section origin and the level may be either as a water depth (negative if above water level), or an elevation (Levels only checked on reach form).

Offsets must be entered in ascending order.

Negative depths represent a height above the water surface.

Values should be entered for every data item at an offset.

Vertical banks have offset values that are the same, but depths are different.

Multiple velocity measurements are also specified with the same offset, but have the same depth.

Overhanging banks should not be included in the data, as the prediction of velocity and habitat suitability will be incorrect if an overhang is underwater.

Negative current meter counts indicate water flowing upstream, as in eddies.

5.2.7 'Gaugings' tab

'Gaugings' holds the corresponding values of flow and water level at all visits. The first row shows the values for the survey (the survey flow and the survey water level), which cannot be edited here; the water level can be edited only on the 'Cross-sections' card, and the flow is calculated from the survey data. The other rows hold the flows and water levels at the rating calibration visits, and these can be edited here. The flow at a rating calibration visit may be measured at only one (the most suitable) cross-section and is calculated before entered here, whereas the water levels must be measured at all cross-sections (see *Data collection during rating calibration visits)*. The 'Gaugings' card has a stage-discharge graph for easy identification of errors. Try entering an addition flow and water level to see how the point shows up on the graph. To delete that point, just blank out the entries. The 'Gaugings' card also holds the *SZF*, and the cross-section minimum is given for comparison.

Pairs of stage and discharge measurements taken at a cross-section at flows other than that of the survey are used to define rating curves.

The units of gaugings are m^3/s or cfs for discharge and metres or feet for stage. The stage must be to the same datum as the water level in the cross-section description.

Every gauging is a pair:

stage in metres or feet   discharge in m^3/s or cfs.

New entries are created when enter is pressed.

Gaugings are deleted when there is no data specified for the stage and discharge. The user will be prompted to save the file when the OK button is pressed.

The rating curve is re-plotted whenever a gauging is added or deleted. This occurs when the user moves the cursor to a new location in the gauging table.

The maximum number of gaugings is 99.

5.2.8 Stage of zero flow

The stage of zero flow is the estimate of the water level that would occur when flow is zero. In riffles, it is normally the lowest point in the cross-section, but for runs and pools it is the lowest point in the cross-section that controls the level of the pool or run, such as the riffle at the tail of a pool.

If no level is specified, the SZF will be assumed the minimum section level.

The SZF is to the same datum as the cross-section water level and is shown as a black line on the cross-section plot .

5.2.9 'Layout' tab

The geometrical layout of the reach can be specified so that the "plan" view is realistic.

This requires either specification of the distance and bearing between cross-sections, and the angle of the cross-section to the reach, or the specification of the coordinates of the zero and end points in each cross-section on Cross-sections tab .

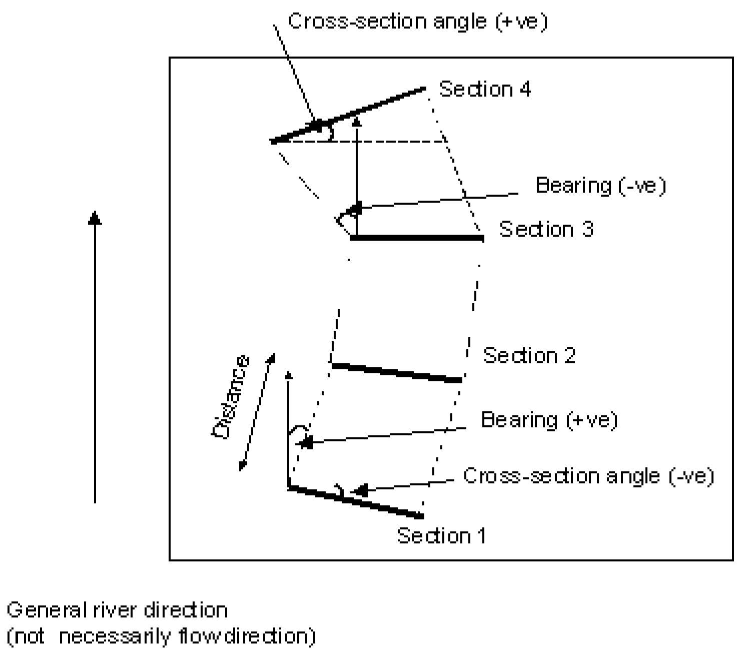
The layout is specified in the Edit/View option of the Edit/Display menu and describes the data for the 'Plan' view (under 'Model) and is only available for representative reach files.

The layout is specified in the Edit/View option of the Edit/Display menu. Habitat mapped data cannot be displayed as a plan view and the data type must be Reach and not Habitat map. However, habitat mapped data can be displayed as a reach simply by changing the survey type from habitat mapping to representative reach. When this is done, the distances between cross-section origins must be specified appropriately.

Representative reach cross-sections should usually be in upstream order - the first section is the downstream section. If data are entered in downstream order, there is no way of altering the order, other than by re-entering the cross-section data in the reverse order.

The layout of the reach can be edited graphically by clicking on the cross-section to be edited when in the Layout page of Edit/View in the Edit/Display menu. Edit "handles" are then displayed. Click and drag the square handle to move, but not rotate, the section. This alters the origin and distance between sections. Click on the circle to rotate the cross-section. As the sections are moved the values of distance, bearing or offset, and angle are displayed in the table. Values can also be entered into the table directly.

The distances here are not used for any calculations but only to plot the plan view (the distances used in the calculations are given on the 'Cross-sections' card.



5.3 River Model File Import

Data can be imported from a text (ASCII) file (*.hab, *.txt), Excel file (*.xls, *.xlsx), RHYHABSIM file (*.rhb) or PHABSIM file (*.rhb). PHABSIM DOS text file (*.ifg), PHABSIM Windows file (*.phb etc.) and saved in a data file with the extension **rhbx**.

The order of data in a text data file is similar to the order used in the field. The text file format is useful because it can be read or written by any text editor or word processor and provides a backup to the **rhbx**. file.

Numerical data should be separated by one or more blanks or tabs and fixed format is not required, but is useful for visible checking.

The order of data is a:

1. Comment lines
2. A reach header describing reach details including attributes
3. A section header followed by
4. A set of cross-section data, ending with “end”.

If an error is detected when importing, the line number is displayed and any errors can be corrected in the original file.

When importing Excel files, you select the sheet to import and the **rhbx**. file will be created with the name of that sheet. Other worksheets in the file can be used to store other information (e.g., habitat mapping).

In this way, multiple reaches can be stored on separate worksheets and imported independently to create **rhbx**. files.

Two types of EXCEL formats are available (text and csv). The first emulates the text format in *.hab files. With the text format, attribute and cross-section names are enclosed in quotes. Microsoft EXCEL uses a single quote to indicate text data and will remove any single quotes when they are the first character in a cell. To get around this behavior you can either use double quotes (") around attribute descriptors or if using single quotes, you must enter two single quotes or alternatively ensure that data items surrounded by single quotes are not the first piece of text in the cell. EXCEL can also change the value you enter when you enter the % sign.

To avoid these restrictions and a second method of data entry can be used. The second method emulates csv format. In this format, attribute and cross-section name quotes need not be used, but if used they will be ignored. The % sign for a habitat weighting value is not required but if used will be ignored. Values need not be entered for all attributes and a blank value is assumed to be zero. **Attribute values must be in the same column at their respective attribute name.**

The important distinction between text and csv excel formats if that with text more than one value or names can be in a single cell. **With the csv format, every value of name must be in its own cell.**

Import and export of text files

When a file is imported, the file is automatically calibrated and any modifications to the calibration data will be lost. However, calibration data can be retained by saving the file as a text (*.hab) file. This stores both the survey data and calibration data.

Other text data files are also used for import and export. These end with the extensions *CON* and *VDF*.

They contain calibration data in the old DOS RHYHABSIM format. When imported these data are stored in the **rhbx** file and these data override the automatic calibration of VDFs, survey flow, and rating curves.

CON - hydraulic calibration parameters - survey flow, rating curve parameters, WSP parameters.

VDF - velocity distribution factors

When importing a habitat text file (*.hab), you are given the choice of importing the existing calibration data, if the files exist. If existing calibration data are not imported, the model is re-calibrated.

5.3.1 Missing values

Missing values for offset, depth, velocity, revs time or attributes can be specified as na. Linear interpolation is used to estimate missing values. Missing values in multi-point velocity measurements are not allowed. If missing values are at start or end of the cross-section, the adjacent values are used.

5.3.2 Comment line(s)

The first line of the text file can contain a title of up to 255 characters. Subsequent lines can contain any information of any length, such as a description of the river, name, and date of survey. The first line will be the Title in the data entry form. The subsequent lines will be in the comments in the data entry form.

A 255 character comment can also be stored with each cross-section. This comment should begin with a // and either be at the end of the cross-section first line or before it. If using Excel, a single quote is required before the //.

Other comments can also be added at the end of any line of data, e.g.,

0 0.35 1.2 // this point is at offset 0 with depth of 0.35 and velocity of 1.2
or at the beginning of a line.

5.3.3 Reach Specification Line

The specification of reach data begins with the word **BED**,

The reach specification line can also define the units of the file. The units can be specified by the keyword **metres** (or **meters**) or **feet**.

an optional keyword **RL**, and a description of up to 10 attributes (or substrates) that will be specified for each cross-section of the reach.

If **RL** is specified, all level data (bed profile, gaugings, SZF, water level) is specified in terms of reduced level.

If RL **is** not specified, gaugings, SZF, and water levels are in terms of a datum, but water depth measurements are relative to the water level, with a depth positive and a height above water level negative.

If bed profile data are specified in terms of reduced level, any water level must also be in terms of the same datum. If bed profile data are in terms of RL and the channel is dry, it is not necessary to supply a water level. Bed profile data or reduced level data are indicated by RL after the keyword BED.

Attribute names are enclosed in single or double quotes so that blanks can be included in names. The order of attribute names is the order in which the corresponding numeric values appear in the cross-section data. e.g.

BED 'BEDROCK' 'BOULDER' 'COBBLE' metres
or
BED "BEDROCK" "BOULDER" "COBBLE" meters
or with EXCEL csv format

BED			BEDROCK	BOULDER"	COBBLE	meters

With the csv format, quotes can be omitted but each attribute must be in separate columns and these must align with their respective attribute values.

If no attributes are recorded, the word BED is sufficient.

Any attribute name may be specified but the following, in upper or lower case, are recognized as substrate descriptors to which habitat suitability criteria apply.

Attributes

An attribute is any characteristic of a point on a cross-section. Attributes are most commonly used to describe substrate composition (% of each type).

Attribute specifications can be added or deleted by first clicking on the list of attributes (blank if none have been entered). Once in this list, attributes can be added, either by selecting one of 8 reserved substrate categories or entering a name, such as INDEX. Any name can be edited or associated with a different substrate category.

The maximum number of attributes for a reach is 10.

Reserved Substrate Names

There are eight basic substrate categories:

Id.	Substrate	Size (mm)
1	Vegetation	-
2	Silt (Mud)	<0.06
3	Sand	0.06-2
4	Fine gravel	2-8
5	Gravel	8-64
6	Cobble	64-264
7	Boulder	>264
8	Bedrock (Rock)	-

If any of the substrate categories are specified, the Check menu option will check that the substrate composition at each point sums to 100%.

If the substrate composition at a point does not sum to 100%, the error can be corrected in the Edit/View option of the Edit/Display menu, although it is better to correct the data on the original file that was imported.

It is possible to get an error message stating that the substrate composition does not sum to 100%, but the Check option indicates that the substrate composition at all points is 100%.

This situation arises when two attributes have been assigned to the same substrate category, usually there will be an 'S' and 'M' attribute with both assigned to mud. To correct this, edit the data (Edit/View option of Edit/Display) and go to the attribute page. Click on the offending attribute (usually S) then the edit button. Assign it to the correct substrate category (e.g., sand), close window, saving the file.

5.3.4 Cross-section Specification First Line

The cross-section first line contains:

- distance
- name
- water level

and optionally

- current meter calibration constants (Levels only not checked) preceded by the keyword MET
- percentage of reach (Habitat mapping)

Distance, name, and percentage

A distance or section ID is specified for each cross-section. The distance and section name identify the location of the cross-section.

If the habitat mapping model is used and cross-section locations selected in habitat types rather than as a representative reach, the percentage of the reach that the cross-section represents is specified, and the cross-section distance will be treated as a station identifier and may be consecutive numbers. The percentage is entered as a number with the percentage sign, either before or after the number (i.e., %5.6 or 5.6%). There should be no blank characters between the number and percent sign. Beware of the way Excel handles % signs. With import as csv style, the % sign is not required.

The section name usually identifies the habitat type and location. The name is enclosed in single (‘) or double (") quotes and can contain a maximum of 20 characters. With import as csv style, the quotes are not required.

The total of the main channel cross-section weights should usually add to 100%.

Cross-section water level

This is the water level at which measurements of water depth and velocity are made. The water level is referenced to an arbitrary datum and need not be referenced to the same datum, although the SZF and gaugings at each cross-section refer to the same datum.

This water level and the flow that is calculated from measured depths and velocities make up the survey stage and measured flow.

The water level at the time of the survey is used to convert measurements of water depth to a common datum. Levels in terms of a common datum are termed reduced levels or elevations. Data taken from maps or topographic surveys are usually already in terms of reduced level or elevation.

If bed profile data are specified in terms of reduced level, any water level must also be in terms of the same datum. If bed profile data are in terms of RL and the channel is dry, it is not necessary to supply a water level.

For habitat mapping, a consecutive number can be specified as a distance rather than the actual distance between cross-sections. If any two consecutive cross-sections have the same distance, they will be regarded as multiple channels of one transect.

For habitat mapping, water levels do not have to be to the same datum. Each cross-section can use its own local datum, usually the top of the peg or pin marking the location of the cross-section.

Each braid or multiple channel is treated independently, and has their own set of levels, survey flows, and datum.

Slope

Cross-section slopes are calculated automatically when a file (*.xls* or *.hab) is imported. If the file is a representative reach, cross-section slopes are calculated from the distances of the cross-section. If the cross-section is the first or last, the slope is the difference in water level divided by the distance to the adjacent cross-section. If the cross section is an intermediate cross-section, the slope is the average of the slopes to the adjacent cross-sections. If the calculated slope is negative, the slope is inferred from Manning's equation and the survey flow, cross-section area, and hydraulic radius:

Slope = (0.06*SurveyFlow/Area/HydraulicRadius^(2/3))^2

If the reach is habitat mapped then the slopes are inferred from the above equation.

The automatically calculated slopes can be edited on the Points page of the Edit/Display Edit/View menu.

Meter constants and velocity

The meter constants are the slope and constant in the equation used to convert the measurement of revolutions/second to a velocity, i.e.

velocity = slope x revolutions/second + constant

If data is recorded as meter revolutions and time, rather than as velocities, the current meter constants are specified after the keyword METER.

The meter constants are two values, a slope and a constant.

If the keyword METER is not specified then data values are assumed to be either depths or depths and velocities rather than depths, revolutions, and times. If METER is omitted, SEFA counts the number of columns entered to determine whether a column of velocities has been entered. If no velocities have been entered then SEFA assumes that these are depth data and estimates velocities based on the assumption that the velocity will be proportional to the hydraulic radius to the power of 2/3.

Text format 25.0 'xsect-02' 7.632 %6.3
Csv format

25.0	xsect-02	7.632	6.3

Distance 'name' water level percentage

If the keyword METER is not followed by meter constants the values for the previous section will be used.

If the keyword METER is not specified then data values are assumed to be velocities rather than revolutions and times.

Text format 25.0 'xsect 2' 7.632 METER 0.680 0.06
Csv format

25.0	xsect 2	7.632	METER	0.680	0.06

Distance 'name' water level meter mult. const.

or if velocities are to be entered

Text format 25.0 'xsect-02' 7.632
Csv format

25.0	xsect-02	7.632

Distance 'name' water level

Cross-section rating data: gaugings

Pairs of stage and discharge measurements (gauging or gagings) taken at a cross-section at flows other than that of the survey are used to define rating curves.

Gaugings are listed after the cross-section first line.

The units of gaugings are m^3/s for discharge and metres for stage. The stage must be to the same datum as the water level in the cross-section description.

The format for gaugings and stage of zero flow is the keyword GAUGING or GAGING followed by the stage and discharge e.g.

GAUGING 9.234 0.537
GAUGING 8.934 0.337
GAUGING 8.254 0.037
SZF 0.702
SURVEY 3.7

or

GAGING 9.234 0.537
GAGING 8.934 0.337
GAGING 8.254 0.037
SZF 0.702
SURVEY 3.7

where the best estimate of the discharge at the time of survey (survey flow) is 3.7 m^3/s.

Up to eight gaugings may be entered.

Cross-section rating data: stage for zero flow

An estimation of the water level at zero flow (SZF) should be made at each cross-section. For riffles, the SZF will usually be the minimum level and it is not necessary to record this. However, for runs and pools the water level at zero flow will be controlled by some downstream feature, usually the minimum level of the downstream bar or head of riffle. This can be estimated by measuring the maximum depth across the bar or riffle head or by leveling to determine the "highest" point on the downstream thalweg. The measurement of stage of zero flow should be in terms of the same datum as the measurement of water level.

The stage at zero flow can be entered after the gaugings. The stage at zero flow is the estimated water level at zero flow and forms part of the rating equation:

Flow = a * (WL-SZF)^b

The stage of zero flow is the estimate of the water level that would occur when flow is zero. In riffles, it is normally the lowest point in the cross-section, but for runs and pools it is the lowest point in the cross-section that controls the level of the pool or run, such as the riffle at the tail of a pool.

Riffles and some runs will be dry when the flow drops to zero so that the stage at zero flow is the section minimum and need not be entered specifically. However, pools are not dry when the flow drops to zero and at zero flow the water level will be the minimum level of the downstream riffle or bar.

If no level is specified, the SZF will be the minimum section level.

The SZF is to the same datum as the cross-section water level and is shown as a black line on the cross-section plot.

5.3.5 Cross-section data

Cross-section data must specify offset and depth pairs. The depth can be in terms of reduced level or more commonly as a depth, where the depth is the height above (negative) or below (positive) the water level. Negative depths represent a height above the water surface.

If velocities are recorded or entered they can be pairs of meter revolution counts and time or a velocity. If the former, the meter calibration constants must be specified.

A cross-section is measured at right angles to the flow. The offset is the distance from the cross-section origin and the level may be either as a water depth (negative if above water level), or an elevation (**RL** specified in text file). Offsets must be entered in ascending order.

If only depth and offset are specified in a cross-section, the flow is assumed to be the survey flow and velocities are calculated assuming a uniform flow distribution (i.e. VDF=1 or constant Manning N).

Vertical banks have offset values that are the same, but with different depths (unlike multipoint velocity measurements).

Overhanging banks should not be included in the data, as the prediction of velocity and habitat suitability will be incorrect if an overhang is underwater.

Measurements across the section must be entered in ascending order of offset with one offset per line and all values (attributes etc.) should be entered for every data item at an offset.

The data items in order are:

For depth data:

4.0	6.0	0	10	90
offset	depth	up to 10 attributes (optional)		

or if velocities are measured:

4.0	6.0	0.96	0	10	90
offset	depth	velocity	up to 10 attributes		

or if revolutions and time is specified.

4.0	.60	40	45.6	0	10	90
offset	depth	revolutions	time	up to 10 attributes		

Values must be entered for every data item at an offset, except for multiple depth velocity measurements, when attributes can be omitted after the first multiple measurement. The same number of attributes must be entered at every section.

Negative current meter counts indicate water flowing upstream, as in eddies.

The keyword END indicates the end of a cross-section and repetition of the keyword END indicates the end of a reach and the end of the input data.

Multipoint velocity measurements

Multi-point velocity measurements (e.g. at 0.2 and 0.8 or 0.2, 0.6 and 0.8 depth) are averaged to give the mean velocity in the vertical.

Multipoint measurements repeat the offset and depth measurement with the velocity reading or count at each point in the vertical. The order (0.2 or 0.8) does not matter. Attributes must be entered with the first velocity measurement, but need not be repeated for the following multi-point measurements.

Multipoint velocity measurements must specify exactly the same offset and depth. Two sets of measurements with the same offset and different depths will be assumed to be a vertical wall.

5.3.6 River Model Text File Examples

This is description of a reach with 2 cross-sections 30.9 m apart.

This is Representative reach data
Comments e.g. date: location

BED				'BE'	'B'	'C'	'G'	'F'	'S'	'SI'	'V' feet
0.0	'Section1'		1.107	**METER**	10.679	0.009					
0.0	-1.0	0	0	0	0	0	0	0	0	0	100
1.5	0.0	0	0	0	0	0	0	0	0	0	100
1.7	0.87	1	24.2	0	0	890	0	0	10	0	0
2.2	1.2	2	25	0	0	90	0	0	10	0	0
3.6	1.04	2	24.5	0	0	80	20	0	0	0	0
3.7	0.97	4	27.7	0	0	80	20	0	0	0	0
4.7	0.78	6	20.9	0	0	80	20	0	0	0	0
5.7	0.52	14	20.7	0	0	30	60	10	0	0	0
6.7	0.30	13	21.2	0	0	30	60	10	0	0	0
8.0	0.24	15	21.1	0	0	20	80	0	0	0	0
9.5	0.24	16	21.4	0	0	50	50	0	0	0	0
11.0	0.22	11	20.2	0	0	50	50	0	0	0	0
12.5	0.20	13	21.1	0	0	20	70	10	0	0	0
14.0	0.23	12	20.9	0	0	20	70	10	0	0	0
15.5	0.29	13	20.2	0	0	20	70	10	0	0	0
17.0	0.38	17	20.9	0	0	20	70	10	0	0	0
18.0	0.47	20	20.5	0	0	10	70	20	0	0	0
19.0	0.63	18	20.5	0	0	10	70	20	0	0	0
20.0	0.65	5	24.1	0	0	10	70	20	0	0	0
21.0	0.84	2	22.5	0	0	20	60	20	0	0	0
21.4	0.78	1	23.2	0	0	30	70	0	0	0	0
21.6	0.0	0	0	60	0	0	0	0	0	0	40

22.0	-1.0	0	0	100	0	0	0	0	0	0	100
END											
30.9	'Section2'		1.128	**METER**	10.68	0.006					
0.0	-1.0	0	0	0	0	0	0	0	0	0	100
1.5	0.0	0	0	0	0	0	0	0	0	0	100
1.7	0.87	1	24.2	0	0	90	0	0	10	0	0
2.2	1.2	2	25	0	0	90	0	0	10	0	0
3.6	1.04	2	24.5	0	0	80	20	0	0	0	0
3.7	0.97	4	27.7	0	0	80	20	0	0	0	0
4.7	0.78	6	20.9	0	0	80	20	0	0	0	0
5.7	0.52	14	20.7	0	0	30	60	10	0	0	0
6.7	0.30	13	21.2	0	0	30	60	10	0	0	0
8.0	0.24	15	21.1	0	0	20	80	0	0	0	0
9.5	0.24	16	21.4	0	0	50	50	0	0	0	0
11.0	0.22	11	20.2	0	0	50	50	0	0	0	0
12.5	0.20	13	21.1	0	0	20	70	10	0	0	0
14.0	0.23	12	20.9	0	0	20	70	10	0	0	0
15.5	0.29	13	20.2	0	0	20	70	10	0	0	0
17.0	0.38	17	20.9	0	0	20	70	10	0	0	0
18.0	0.47	20	20.5	0	0	10	70	20	0	0	0
19.0	0.63	18	20.5	0	0	10	70	20	0	0	0
20.0	0.65	5	24.1	0	0	10	70	20	0	0	0
21.0	0.84	2	22.5	0	0	20	60	20	0	0	0
21.4	0.78	1	23.2	0	0	30	70	0	0	0	0
21.6	0.0	0	0	60	0	0	0	0	0	0	40
22.0	-1.0	0	0	0	0	0	0	0	0	0	0
END											
END											

This is description of a reach with 2 cross-sections, with the first representing 60% of the reach area and the second 40%.

This is **HABITAT MAP** data.

Comments e.g. date: location

BED				'BE'	'B'	'C'	'G'	'F'	'S'	'SI'	'V' feet
1	'Section1'	1.107		**METER**	10.679	0.009	**%**60				
0.0	-1.0	0	0	0	0	0	0	0	0	0	100
1.5	0.0	0	0	0	0	0	0	0	0	0	100
1.7	0.87	1	24.2	0	0	890	0	0	10	0	0
2.2	1.2	2	25	0	0	90	0	0	10	0	0
3.6	1.04	2	24.5	0	0	80	20	0	0	0	0
3.7	0.97	4	27.7	0	0	80	20	0	0	0	0
4.7	0.78	6	20.9	0	0	80	20	0	0	0	0
5.7	0.52	14	20.7	0	0	30	60	10	0	0	0
6.7	0.30	13	21.2	0	0	30	60	10	0	0	0
8.0	0.24	15	21.1	0	0	20	80	0	0	0	0
9.5	0.24	16	21.4	0	0	50	50	0	0	0	0
11.0	0.22	11	20.2	0	0	50	50	0	0	0	0
12.5	0.20	13	21.1	0	0	20	70	10	0	0	0
14.0	0.23	12	20.9	0	0	20	70	10	0	0	0
15.5	0.29	13	20.2	0	0	20	70	10	0	0	0
17.0	0.38	17	20.9	0	0	20	70	10	0	0	0
18.0	0.47	20	20.5	0	0	10	70	20	0	0	0
19.0	0.63	18	20.5	0	0	10	70	20	0	0	0

```
20.0  0.65       5   24.1  0      0       10     70    20  0   0   0
21.0  0.84       2   22.5  0      0       20     60    20  0   0   0
21.4  0.78       1   23.2  0      0       30     70    0   0   0   0
21.6  0.0        0   0     60     0       0      0     0   0   0   40
22.0  -1.0       0   0     100    0       0      0     0   0   0   100
END
2     'Section2'     1.128 METER  10.68   0.006  %40
0.0   -1.0       0   0     0      0       0      0     0   0   0   100
1.5   0.0        0   0     0      0       0      0     0   0   0   100
1.7   0.87       1   24.2  0      0       90     0     0   10  0   0
2.2   1.2        2   25    0      0       90     0     0   10  0   0
3.6   1.04       2   24.5  0      0       80     20    0   0   0   0
3.7   0.97       4   27.7  0      0       80     20    0   0   0   0
4.7   0.78       6   20.9  0      0       80     20    0   0   0   0
5.7   0.52       14  20.7  0      0       30     60    10  0   0   0
6.7   0.30       13  21.2  0      0       30     60    10  0   0   0
8.0   0.24       15  21.1  0      0       20     80    0   0   0   0
9.5   0.24       16  21.4  0      0       50     50    0   0   0   0
11.0  0.22       11  20.2  0      0       50     50    0   0   0   0
12.5  0.20       13  21.1  0      0       20     70    10  0   0   0
14.0  0.23       12  20.9  0      0       20     70    10  0   0   0
15.5  0.29       13  20.2  0      0       20     70    10  0   0   0
17.0  0.38       17  20.9  0      0       20     70    10  0   0   0
18.0  0.47       20  20.5  0      0       10     70    20  0   0   0
19.0  0.63       18  20.5  0      0       10     70    20  0   0   0
20.0  0.65       5   24.1  0      0       10     70    20  0   0   0
21.0  0.84       2   22.5  0      0       20     60    20  0   0   0
21.4  0.78       1   23.2  0      0       30     70    0   0   0   0
21.6  0.0        0   0     60     0       0      0     0   0   0   40
22.0  -1.0       0   0     0      0       0      0     0   0   0   0
END
END
```

This is description of a reach with 2 cross-sections 30.9 m apart with no velocity or substrate measurements.

With EXCEL csv format

BED		feet		BE	B	C	G	F	S	SI	V
1	Section1	1.107		METER	10.679	0.009	0.6				
0	-1	0	0								100
1.5	0	0	0								100
1.7	0.87	1	24.2			890			10		
2.2	1.2	2	25			90	0		10		
3.6	1.04	2	24.5			80	20				
3.7	0.97	4	27.7			80	20				
4.7	0.78	6	20.9			80	20				
5.7	0.52	14	20.7			30	60	10			
6.7	0.3	13	21.2			30	60	10			
8	0.24	15	21.1			20	80	0			
9.5	0.24	16	21.4			50	50	0			
11	0.22	11	20.2			50	50	0			
12.5	0.2	13	21.1			20	70	10			

14	0.23	12	20.9			20	70	10			
15.5	0.29	13	20.2			20	70	10			
17	0.38	17	20.9			20	70	10			
18	0.47	20	20.5			10	70	20			
19	0.63	18	20.5			10	70	20			
20	0.65	5	24.1			10	70	20			
21	0.84	2	22.5			20	60	20			
21.4	0.78	1	23.2			30	70	0			
21.6	0	0	0	60							40
22	-1	0	0	100							100
END											
2	Section2		1.128	METER	10.68	0.006	0.4				
0	-1	0	0								100
1.5	0	0	0								100
1.7	0.87	1	24.2			90			10		
2.2	1.2	2	25			90			10		
3.6	1.04	2	24.5			80	20	0			
3.7	0.97	4	27.7			80	20	0			
4.7	0.78	6	20.9			80	20	0			
5.7	0.52	14	20.7			30	60	10			
6.7	0.3	13	21.2			30	60	10			
8	0.24	15	21.1			20	80	0			
9.5	0.24	16	21.4			50	50	0			
11	0.22	11	20.2			50	50	0			
12.5	0.2	13	21.1			20	70	10			
14	0.23	12	20.9			20	70	10			
15.5	0.29	13	20.2			20	70	10			
17	0.38	17	20.9			20	70	10			
18	0.47	20	20.5			10	70	20			
19	0.63	18	20.5			10	70	20			
20	0.65	5	24.1			10	70	20			
21	0.84	2	22.5			20	60	20			
21.4	0.78	1	23.2			30	70				
21.6	0	0	0	60							40
22	-1	0	0								100
END											
END											

This is **REACH** depth data.

```
BED
0.0       'Section1'     1.107
0.0       -1.0
1.5       0.0
```

```
1.7     0.87
2.2     1.2
3.6     1.04
3.7     0.97
4.7     0.78
5.7     0.52
6.7     0.30
8.0     0.24
9.5     0.24
11.0    0.22
12.5    0.20
14.0    0.23
15.5    0.29
17.0    0.38
18.0    0.47
19.0    0.63
20.0    0.65
21.0    0.84
21.4    0.78
21.6    0.0
22.0    -1.0
END
30.9    'Section2'    1.128
0.0     -1.0
1.5     0.0
1.7     0.87
2.2     1.2
3.6     1.04
3.7     0.97
4.7     0.78
5.7     0.52
6.7     0.30
8.0     0.24
9.5     0.24
11.0    0.22
12.5    0.20
14.0    0.23
15.5    0.29
17.0    0.38
18.0    0.47
19.0    0.63
20.0    0.65
21.0    0.84
21.4    0.78
21.6    0.0
22.0    -1.0
END
END
```

This is **REACH** reduced level data.

BED	RL
0	'Section 1'
0	97.654
1.5	96.654
1.7	95.784
2.2	95.454
3.6	95.614

```
     3.7        95.684
     4.7        95.874
     5.7        96.134
     6.7        96.354
       8        96.414
     9.5        96.414
      11        96.434
    12.5        96.454
      14        96.424
    15.5        96.364
      17        96.274
      18        96.184
      19        96.024
      20        96.004
      21        95.814
    21.4        95.874
    21.6        96.654
      22        97.654
END
    30.9  'Section 2'
       0        97.654
     1.5        96.654
     1.7        95.784
     2.2        95.454
     3.6        95.614
     3.7        95.684
     4.7        95.874
     5.7        96.134
     6.7        96.354
       8        96.414
     9.5        96.414
      11        96.434
    12.5        96.454
      14        96.424
    15.5        96.364
      17        96.274
      18        96.184
      19        96.024
      20        96.004
      21        95.814
    21.4        95.874
    21.6        96.654
      22        97.654
END
END
```

5.4 Braided or multi-channel reach data entry

Braided or multi-channel rivers are modeled in the same way as habitat mapped reaches of single channel rivers. However, the proper extrapolation of multichannel reaches to flows higher than the survey flow requires some special attention to prevent the channels extending indefinitely, when they would actually coalesce.

Water surface profile modeling is not possible and prediction of water levels is based on stage-discharge curves for each braid or channel.

The survey procedure involves selecting cross-sections that are representative of the general character of the river. This may be cross-sections at regular intervals.

The channels of each cross-section are surveyed, as well as the banks between. Each channel is treated separately and the division between two adjacent channels can be a vertical wall if the last offset of one channel is the same point as the first offset of the next, or can be a high point that will not be inundated at any of the flows modeled.

The same cross-section distance and weight applies to every braid or channel on the cross-section. In fact, the similarity of any two cross-section distances is used to indicate that the reach is braided.

Braided reach data can be edited or even entered using the Edit/Display>>Edit/View menu. However, the recommended method is to import an EXCEL or ASCII file (e.g., *.xls, *.xlsx, *.hab). If a braided reach is entered or edited with Edit/Display>>Edit/View menu, the reach should be exported then imported to ensure that the calibration process is carried out correctly.

Data for a channel of a braided river might be:

Lower Waitaki Survey at Ferry Road on 9/7/01 with survey flows 10/7/01, 11/7/01, 12/7/01

Bed				'B'	'C'	'G'	'F'	'S'	'M'	'V' metres
1.000	'Channel1/2'		9.783	Meter	0.675	0.010	%8.333			
Gauging	9.308	9.555	152.500							
Gauging	9.190	4.868	122.200							
Gauging	9.037	1.972	85.500							
SZF	8.623	38.802								
130.000	-0.60	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
131.000	-0.50	0	0.0	0.0	20.0	80.0	0.0	0.0	0.0	0.0
133.500	0.00	0	0.0	0.0	20.0	80.0	0.0	0.0	0.0	0.0
135.000	0.25	14	20.0	0.0	30.0	70.0	0.0	0.0	0.0	0.0
136.000	0.81	36	20.6	0.0	30.0	70.0	0.0	0.0	0.0	0.0
170.000	0.86	37	20.4	0.0	40.0	60.0	0.0	0.0	0.0	0.0
175.000	0.92	34	20.5	0.0	30.0	70.0	0.0	0.0	0.0	0.0
180.000	0.93	25	20.5	0.0	20.0	80.0	0.0	0.0	0.0	0.0
185.000	0.54	10	22.5	0.0	0.0	0.0	30.0	70.0	0.0	0.0
190.000	0.25	5	20.0	0.0	40.0	60.0	0.0	0.0	0.0	0.0
196.000	0.00	0	0.0	0.0	20.0	80.0	0.0	0.0	0.0	0.0
200.000	-0.01	0	0.0	0.0	20.0	80.0	0.0	0.0	0.0	0.0
205.000	-0.01	0	0.0	0.0	20.0	80.0	0.0	0.0	0.0	0.0
210.000	-2.00	0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
210.000	-3.00	0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
end										
1.000	'Channel1/3'		9.905	Meter	0.675	0.010	%8.333			
Gauging	9.495	115.329	152.500							
Gauging	9.410	106.837	122.200							
Gauging	9.392	73.197	85.500							
SZF	6.730	0.000								
210.000	-3.00	0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
210.000	-2.00	0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
216.000	-0.01	0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0

217.000	0.00	0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
220.000	0.06	5	20.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
225.000	0.14	20	23.8	0.0	5.0	95.0	0.0	0.0	0.0	0.0
230.000	0.14	20	26.4	0.0	10.0	90.0	0.0	0.0	0.0	0.0
235.000	0.30	30	24.0	0.0	15.0	85.0	0.0	0.0	0.0	0.0

310.000	0.37	30	21.5	0.0	0.0	0.0	0.0	0.0	0.0	100.0
315.000	0.18	15	22.5	0.0	0.0	0.0	0.0	0.0	0.0	100.0
320.000	0.13	11	22.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
325.000	0.22	17	23.3	0.0	0.0	0.0	0.0	0.0	0.0	100.0
328.000	0.00	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
329.000	-1.00	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0

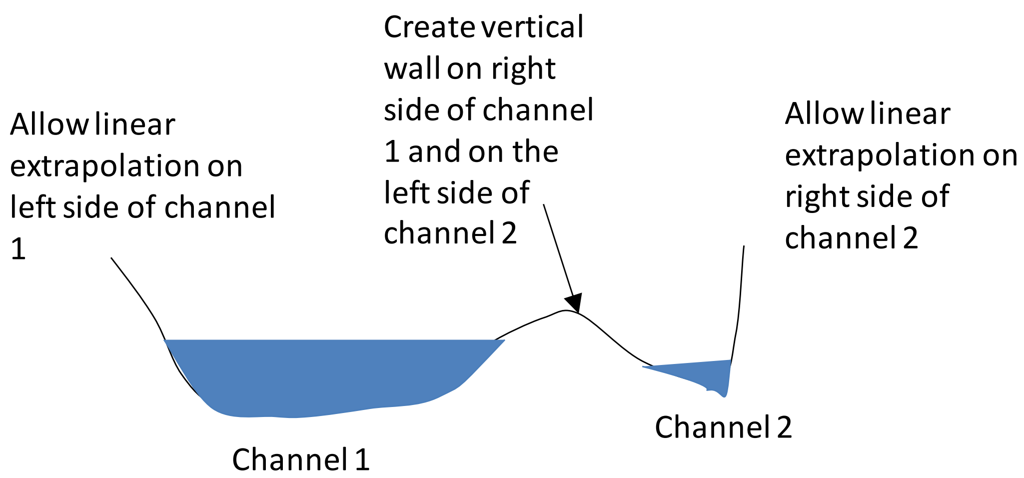
end

The calibration data:

Gauging	9.308	9.555	152.500
Gauging	9.190	4.868	122.200
Gauging	9.037	1.972	85.500
SZF	8.623	38.802	

means that the braid level was 9.308 when the braid flow was 9.555 and total river flow was 152.5. The braid stopped flowing (SZF) at a level of 8.623 when the river flow was 38.802.

The proper extrapolation of multi-channel reaches to flows higher than the survey flow requires some special attention to prevent the channels extending indefinitely, when they would actually coalesce. SEFA assumes that the left and right sides of channels will be extrapolated linearly, if the side slope is greater than the minimum side slope (specified as the slope below which a vertical bank will be created in File>>Preference>>Calculation: default = 0.05). The diagram below shows that linear extrapolation for the left bank in channel 1 would be a valid assumption and similarly for the right bank of channel 2. However, because the two channels are specified separately with the high point between the two as the separation point, there should be no extrapolation of the right bank of channel 1 and no extrapolation of the left bank of channel 2. To prevent extrapolation, the data file should specify an artificial vertical wall at the end of channel 1 and at the beginning of channel 2.



The artificial vertical walls in the above example are highlighted in the above example.

5.4.1 Calibration for multiple (braided) channels

The variation of water level with flow must be determined by calibration for each channel. Calibration data for braided cross-sections records the stage, braid flow, and river flow.

It is also necessary to determine the river flow at which the braid ceases flowing. This is termed "main flow at zero braid flow" and is entered with the stage of zero flow.

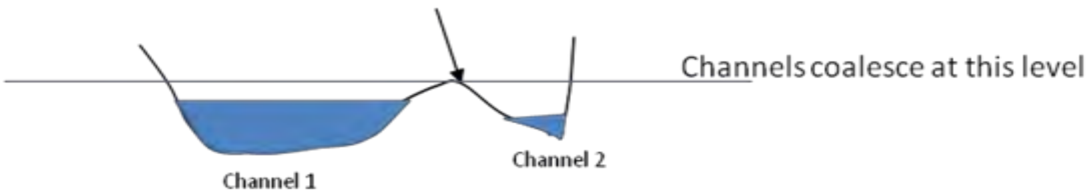
The survey flow must be set for each braid, by checking the vary flow between sections option in the "survey flow" dialogue.

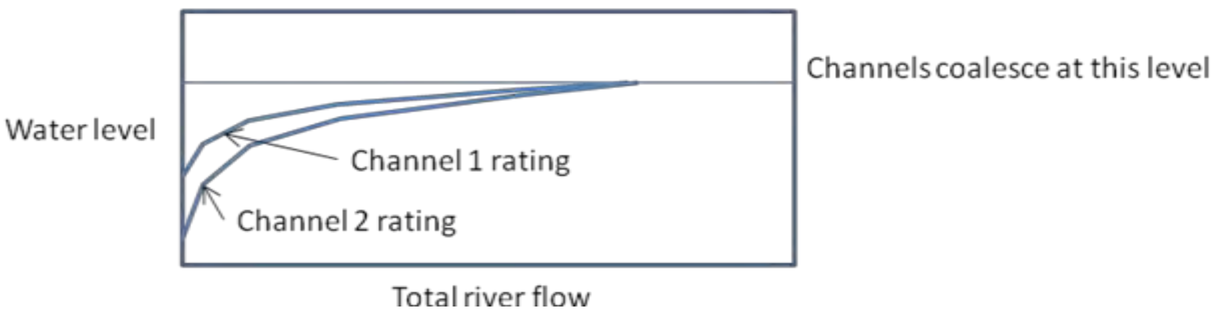
The analysis of data from a braided reach is the same as in a single channel reach, with water depths, velocities, and habitat suitability summed across each braid in the cross-section and then over the reach.

Results are usually tabulated for each braid with the cross-section total shown in bold after the braids.

Plotting routines will display each braid separately and it is not possible to show the full cross-section in one display unless the data are re-arranged for that specific purpose.

If a multi-channel reach is to be used for high flow extrapolation, it should be ensured that the rating curves of the braids in any one transect predict the same water level when the braids coalesce, as shown below.





5.4.2 Analysis for multiple reaches

When characteristics of a multiple reaches are summed, each cross-section is weighted by the habitat weight and the total reach weight is the sum of the cross-section weights. With multiple reaches, the sum habitat weights for each reach need not sum to 1 and the weights can be used to weight reaches according to the length of river they represent. For example, if the survey was of two reaches upstream and downstream of a tributary. The reach upstream of the tributary might represent 40% of the length of river and the downstream reach might represent 60%. The sum of the habitat weights for the upstream reach would sum to 0.4 and the sum of the downstream reach weights would sum to 0.6. When the two reaches are analyzed together, the proportion of the reach modeled will be given as 100%.

If the habitat weights of two reaches each sum to 100%, each reach will be given equal weight and the proportion of the reach modeled will be given as 200%.

6 Time Series Import Data

This description also applies to importing DO calibration data using the menus Dissolved Oxygen>>Reach>>Open DO file and Calibrate.

Data should be in a row by column matrix with each row representing a sampling occasion and each column containing the date or environmental data.

The data should follow a line giving the column names. Columns can be delimited by blanks, tabs, or commas.

SEFA can read text files delimited by commas, tabs or blanks (single blank between data values), and EXCEL files. The EXCEL files have .XLS or XLSX as the extension (the characters following the last period). SEFA will automatically identify the delimiter in text files, but the normal convention is that the extension for comma delimited files is .CSV, for tab delimited files TXT, and for files with blanks between data values .DAT. SEFA requires the text file extension to be either CSV, TXT, or DAT.

If an Excel file is opened, a list of worksheets is displayed and any one can be selected.

6.1 Date formats

A number of common date formats are recognized in the input file. When displayed, date formats on graphs can be changed using the View/Display>>Graph options menu.

The time is specified with the date with a blank separating the date from the time.

The time must consist of two or three numbers, separated by the character defined by the Time Separator variable set in Windows Settings>>Regional and Language, optionally followed by an AM or PM indicator, also set in Windows Settings>>Regional and Language. The Time Separator is usually a colon :, but the AM/PM indicator can be either AM or a.m. The numbers represent hour, minute, and (optionally) second, in that order. If the time is followed by a.m or p.m, it is assumed to be in 12-hour clock format. If no AM or PM indicator is included, the time is assumed to be in 24-hour clock format.

Some examples of input file date/time formats are:

3/03/1945

3/3/45

3-May-75

3-May-1975

6-August- 2001

26-Aug-01

26 August 2001

13/02/1945 12:00

14/2/45 2:00:01 p.m.

3-May-75

3-May-1975 3:45 a.m.

6-August- 2001 14:55:00

26-Aug-01 6:00:00 PM

26 August 2001 13:10:10

2007-02-25 (USGS)

You can also use the following US style dates.

02/13/1945 12:00

2/14/45 2:00:01 p.m.

May-3-75

May-3-1975 3:45 a.m.

August- 6-2001 14:55:00

Aug-26-01 6:00:00 PM

August 26 2001 13:10:10

If the year is 25 or less, 2000 is added to make it a four-digit year, if the year is > 25 then 1900 is added.

In all cases, the year can be either two or 4 digits. If the year is 25 or less, 2000 is added to make it a four-digit year, if the year is > 25 then 1900 is added.

Hydrological data imported as a text file from the USGS is a little more complicated to import directly. There are three ways:

1. Edit the beginning of the USGS text file so that the first line contains the column descriptors (e.g., agency_cd site_no datetime 02_00060_0000302_00060_00003_cd) and delete the fortran format line that follows the column descriptors (e.g., 5s 15s 20d 14n 10s). You could also import the text file into Excel and delete unnecessary columns of data.

2. Edit the USGS file so that there is a # sign at the start of the line following the column descriptors (e.g., agency_cd site_no datetime 02_00060_0000302_00060_00003_cd) so that it reads something like (e.g., #5s 15s 20d 14n 10s). Then in the box labelled Ignore lines beginning enter a #. The data should then begin with the column header followed by the data. Click OK to import.
3. Import the UGS file into SEFA. Scroll the lines so that the top line of the display shows the column names (as above), set the ignore lines beginning character to the first character of the format line (i.e., 5 in the example above). This file will import but may be slow because of all the unnecessary columns.

6.2 Order of columns and lines

An example of the first lines of a comma delimited stream flow data file for SEFA is:

Daily discharge in cubic feet/second (cfs)

Watershed area of 1493 square mines

Dam break flood on 1 January 1989 with a peak discharge of 66,000 cfs

Date ,H 09408150 VIRGIN RIVER NEAR HURRICANE, UT

1967-03-07, 161

1967-03-08, 160

1967-03-09, 161

1967-03-10, 155

1967-03-11, 154

1967-03-12, 155

1967-03-13, 160

1967-03-14, 182

1967-03-15, 169

------- etc. -------

The first lines of a stream flow data file may contain information not used by SEFA. In the example above this is the first three lines. In this example, the date is in the first column followed by a delimiter (comma, tab, or blank), followed by the discharge in the second column. The line immediately above the first line with data should contain an identifier for each column.

In the example above, this is ‘Date’ for the date column and ‘H 09408150 VIRGIN RIVER

NEAR HURRICANE, UT’ for the discharge column.

The format for the above file with blank delimiters must have the following format: ‘date blank discharge’ and there must not be blanks in the column title. An example of a stream flow file with blank delimiters is:

date H09408150VIRGINRIVERNEARURRICANE.UT

1967-03-07 161

1967-03-08 160

1967-03-09 161

1967-03-10 155

1967-03-11 154

1967-03-12 155

1967-03-13 160

1967-03-14 182

1967-03-15 169

1967-03-16 148

1967-03-17 148

1967-03-18 172

Note: There is only one blank between the date and discharge and no blanks in the column title.

Multiple columns may be used as shown below. The data shown is the first 15 and last 8 lines of a 36,617 line data file. In this data file, the first five lines are skipped and not used by SEFA. The column labels used by SEFA are ‘date’ for the date column,’04_00060_00001’ for the first stream flow data column, ‘04_00060_00002’ for the second and,’04_00060_00003’ for the third.

SEFA uses these labels to identify the columns. There is a large amount of missing data in the first two stream flow data columns. Blank delimiters could be used for the missing data, but it is not advisable as it is difficult to ensure there is the same number of blanks for in each line.

USGS 02080500 ROANOKE RIVER AT ROANOKE RAPIDS, NC

DD parameter statistic Description

04 00060 00003 Discharge, cubic feet per second (Mean)

04 00060 00001 Discharge, cubic feet per second (Maximum)

04 00060 00002 Discharge, cubic feet per second (Minimum)

date,04_00060_00001,04_00060_00002,04_00060_00003

1/1/1912,,,9060

1/2/1912,,,11400

1/3/1912,,,10900

1/4/1912,,,9960

1/5/1912,,,9500

1/6/1912,,,8630

1/7/1912,,,7010

1/8/1912,,,5500

1/9/1912,,,5140

---- etc.----

3/19/2012,3400,3300,3330

3/20/2012,3420,3360,3390

3/21/2012,3440,3360,3400

3/22/2012,3470,3380,3410

3/23/2012,4590,3360,3430

3/24/2012,4590,4260,4330

3/25/2012,4330,4210,4260

3/26/2012,7990,4260,4380

6.3 Order of data

Data can be in any order in the input file. If data are not in date order, they are sorted into date order before any analysis.

7 Time Series>>Select AWS>>Flow Relationship Import

AWS/Flow relationships can be imported either from a SEFA file in which the AWS/Flow relationship has been saved or a text file with the format specified below.

Text file data format

The data should follow a line giving a column name for the relationship in the first column. Column names for the other columns are optional. The columns can be separated by blanks, tabs, or commas.

Data should be in a row by column matrix with each row containing a pair of flow, AWS and wetted width values. The flow should be in the first column, the AWS value in the second and the width in the third.

SEFA can read comma delimited files "*.CSV", text files with blanks between data values "*.TXT, *.DAT, or Excel files "*.XLS" or "XLSX".

If an Excel file is opened, a list of worksheets is displayed and any one can be selected.

When the file is imported, it is listed in the available relationships along with any relationships that have previously been calculated for the rhbx file.

When an available relationship is selected, the values are listed and the relationship is shown graphically.

Example:

Common bully - flow m3/s and AWS m2/m and width (m)	AWS (m2/m)	Width (m)
0	0.806	2.50
1	9.915	5.50
2	9.169	6.19
3	7.966	6.67
4	6.833	7.05
5	5.734	7.36
Brown trout (< 100 mm)		
0	0	2.50
1	7.497	5.50
2	7.94	6.19
3	7.582	6.67
4	6.433	7.05
5	5.266	7.36
6	4.46	7.64
7	3.807	7.88
8	3.198	8.10

	9	2.678	8.30

8 Habitat Suitability File Import

Habitat suitability files (either EXCEL (*. xls, *.xlsx) or text (*.prf)) are imported into a suitability curve library (*.LIB), using the dialogue found by selecting menu HSC>>Select Habitat Suitability Curves.

The first line contains a description of the species and life stage to which the habitat suitability criteria apply. The description can include upper and lower-case letters. A reference to the source of the habitat suitability curves can also be included. This reference is displayed (optionally) when the curves are displayed or when the results of habitat analyses are presented graphically.

The source of the habitat suitability data is entered on the first line following a double slash i.e.,//

The remaining lines contain a keyword specifying whether the numbers that follow are weighting factors, depths, velocities or substrate. However, any keyword can be used, but must be associated with a calculated variable (Depth, velocity, Froude number etc.) or an attribute when selected for use with a file.

Numerical data are separated by one or more blanks. TAB characters are acceptable but beware of other non-standard control characters.

The recognized keywords are WEIGHT DEPTH VELOCITY SUBSTRATE but only the first 3 letters are necessary. Other descriptors can be used to describe user specified habitat variables, such as COVER or INDEX, and these must be associated with surveyed attributes of a file when the suitability curve is selected.

Values of depth, velocity and substrate and user specified habitat variables must increase. Any number of points can be used to define depth and velocity and other habitat variables for habitat suitability curves. Substrate categories can be specified either as a single suitability weight for each of the 8 reserved substrate categories. Alternatively, if substrate indices were assessed at each measurement point, the suitability criterion name should be specified as INDEX, or any name other than the recognized keywords, with any number of index values and their corresponding suitability weights.

Values of habitat suitability are interpolated linearly from these data. If a depth or velocity is outside the range specified in the criteria, habitat suitability is that of nearest criteria (i.e. horizontal extrapolation).

Eight reserved substrate categories are specified by a code number. The types and their respective code numbers are:

1 Vegetation

2 Silt (Mud)

3 Sand

4 Finegravel

5 Gravel

6 Cobble

7 Boulder

8 Bedrock (Rock)

Substrate values can also be specified as a substrate index taking values of between 1 and 8.

On the line below that specifying depth, velocity or substrate, the keyword WEIGHT must be given and be followed by a set of weighting values of between 0 and 1.

The number of weights specified must equal the number of depths velocities or substrates.

Habitat suitability specification ends with END.

If the suitability weight of suitable habitat is 1 and the weight of unsuitable habitat is 0, the weighted usable area will be the area of ideal habitat (i.e. where the velocities, depths and substrate meet the criteria specified by the weight of 1). If weights of between and including 0 and 1 are used then the area of habitat is the area weighted suitability AWS.

Substrate categories are nominal and their definitions can be modified to suit user needs, such as spawning or cover suitability. For example, the attribute types may be reassigned to the different cover attributes used by adult brown trout:

Nominal attribute	Cover attribute	Suitability weight
Vegetation	Debris	.5
Silt	Bank cover	0.8
Sand	No cover	0
Boulder	Boulder	0.8
Bedrock	Bedrock crevice	1

The reach specification would read:

BED 'Vege' 'Silt' 'Sand' 'Boulder' 'Bedrock'

but would in effect mean:

BED 'Debris' 'bank cover' 'no cover' 'Boulder' 'Bedrock crevice'.

The presence of cover elements would be recorded at each measurement point under their respective nominal attribute names.

The habitat suitability curves would include substrate weightings that reflect cover suitability:

Brown trout cover//example data only

VELOCITY	0	.25	.26	.28	.3	.6	.7	.8	.9	1.0	1.2	2.0
WEIGHT	1	1	.9	.8	.65	.32	.3	.25	.2	.1	0.05	0
DEPTH	0	.2	.5	1								
WEIGHT	0	.5	1	1								
SUBSTRATE	1	2	3	4	5	6	7	8				
WEIGHT	.5	.8	0	0	0	0	.8	1				

Depth and velocity suitability could be specified, as in the example, or set to 1, if depth and velocity does not influence cover.

Habitat evaluation would then determine how cover changes with flow. For example, the effect of flow changes on the area of submerged objects can be determined. The object is given the attribute 'Object' and its occurrence is recorded as either a 0 or 100. Habitat evaluation would evaluate the area of 'Objects' that were submerged.

Habitat suitability criteria for depth, velocity, substrate and user specified habitat variables can be displayed by double clicking on the name of appropriate suitability curve when selecting suitability curves.

8.1 Example of habitat suitability file

```
Brown trout adult//Bovee 1978
VELOCITY 0 .25 .26 .28 .3 .6 .7 .8 .9 1.0 1.2 2.0
WEIGHT 1 1 .9 .8 .65 .32 .3 .25 .2 .1 0.05 0
DEPTH  .23 0.3 0.6 .76
WEIGHT  0 .6 .72 1
SUBSTRATE 1 2 3 4 5 6 7 8
WEIGHT 0.3 0 .95 1 1 1 .15 0
END
```

```
Food producing//Waters 1976

VELOCITY 0.15 0.30 0.64 0.85 1.20 1.30
WEIGHT  0 .58 1  1 .4 0
DEPTH .06 .09 0.20 0.80 1.00 1.22 1.525 2.00
WEIGHT 0 .65 1  1 .9 .7 .45 0
SUBSTRATE 1 2 3 4 5 6 7 8
WEIGHT .3 .2 0 .2 .6 1 .8 .6
END
```

Or with a substrate index, rather than the 8 substrate categories

```
Food producing//(Waters 1976
VELOCITY 0.15 0.30 0.64 0.85 1.20 1.30
WEIGHT  0 .58 1  1 .4 0
DEPTH .06 .09 0.20 0.80 1.00 1.22 1.525 2.00
WEIGHT 0 .65 1  1 .9 .7 .45 0
SUBSTRATE 1   2   3  3.5  4   5.5   7   8
WEIGHT    0.3  0.2  0   0  0.2  0.6   1  0.6
END
```

Example of habitat suitability criteria with the user specified variable; COVER.
Shortfin eel < 300mm //Jowett & Richardson 2008

Depth	0	0.08	0.16	0.25	0.38	0.6		
Weight	0	0.84	1	1	0.91	0		
Velocity	0	0.03	0.05	0.4	0.6	0.8	0.9	1
Weight	0	0.95	1	1	0.6	0.3	0.15	0
Substrate	1	2	3	4	5	6	7	8
Weight	1	1	0.6	0.5	0.5	1	1	0.82
Cover	0	2	3	4	5	6	7	8
Weight	0	1	0.6	0.5	0.5	1	1	0.82
end								

Substrate habitat suitability is calculated from the substrate categories. The substrate habitat suitability curve describes the suitability of each substrate category, and the substrate suitability at measurement point is the sum of the suitability for each category multiplied by the percentage of that substrate category at the point.

Alternatively, if substrate indices were assessed at each measurement point, the suitability criterion name should be specified as INDEX, or any name other than the recognized keywords, with any number of index values and their corresponding suitability weights.

9 ANALYSIS OF RIVER MODEL

9.1 Checking data

A check of the data should be the first stage of any analysis.

The rhbx file is checked to ensure that:

- substrate descriptors (if any) are recognized and associated with the correct substrate category
- section distances increase in order upstream
- cross-section offsets increase across the section
- stage at zero flow is greater than the section minimum
- stage for gaugings is greater than the section minimum

Warning messages are issued where data may not be correct. In many instances, these warnings can be ignored but they may indicate a mistake in data entry. Warnings include:

- unreasonably high velocities
- negative velocities
- undefined water's edge (no measurement at zero depth)
- measurements with the same offset but with different depths or attributes
- substrate values at a point do not add to 100%
- cross-section percentages do not add to 100%

9.1.1 Substrate names

There are eight reserved substrate categories:

Id.	Substrate	Size (mm)
1	Vegetation	-
2	Silt (Mud)	<0.06
3	Sand	0.06-2
4	Fine gravel	2-8
5	Gravel	8-64
6	Cobble	64-264
7	Boulder	>264
8	Bedrock (Rock)	-

If any of the substrate categories are specified, the Check menu option will check that the substrate composition at each point sums to 100%. The substrate composition should add to 100%, otherwise the calculation of habitat suitability and sediment functions will be incorrect.

If the substrate composition at a point does not sum to 100%, the error can be corrected in the Edit/View option of the Edit/Display menu.

It is possible to get an error message stating that the substrate composition does not sum to 100%, but the Check option indicates that the substrate composition at all points is 100%.

This situation arises when two attributes have been assigned to the same substrate category, usually there will be an 'S' and 'M' attribute with both assigned to mud. to correct this, edit the data (Edit/View option of Edit/Display) and go to the attribute page. Click on the offending attribute (usually S) then the edit button. Assign it to the correct substrate category (e.g., sand), close window, saving the file.

9.1.2 Checking calibration flows and levels

If calibration flows and associated water levels are specified, the checking procedure produces a set of tables that can be used to check the consistency of flows and water levels between sections.

This table lists the survey and calibration flows and stages, and then shows the stage change in mm change per m^3/s between the calibration flow and water level and the survey flow and water level.

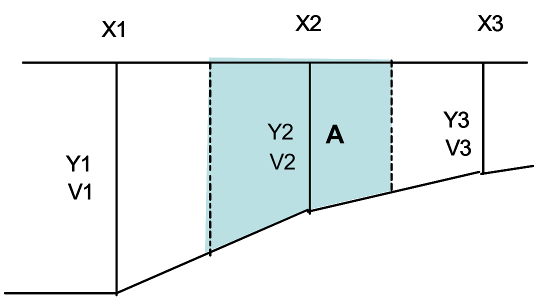
mm stage change per m^3/s flow change = (Survey water level- Calibration water level)/(Survey flow - Calibration flow)*1000

Usually, the stage change for unit change in flow is reasonably consistent from cross-section to cross-section. Large departures from the mean indicate the possibility of an error. Departures of more than twice the mean or less than half the mean are highlighted.

The tables list calibration flows in the order that they are entered in the data file.

9.2 <u>Calculation of flows</u>

Flow for each cross-section is calculated by multiplying the velocity at each point in the cross-section by the cross-section area that it represents. If more than one velocity is measured at a point (e.g., at 0.2, 0.6 and 0.8 of depth), the velocities are averaged. The cross-section area between the mid-points of the adjacent points, calculated assuming linear interpolation. This method of calculation is consistent with that used for the calculation of AWS, where the CSI is weighted by the distance between adjacent mid-points.



$$A = \frac{\left((X2 - X1) \times \left(\frac{Y1 + 3Y2}{2} \right) + (X3 - X2) \times \left(\frac{3Y2 + Y3}{2} \right) \right)}{4}$$

$$Q = \frac{\frac{(V1 + V2)}{2} + V2}{2} \times \frac{\left((X2 - X1) \times \frac{(Y1 + 3Y2)}{2} \right)}{4} + \frac{\frac{(V3 + V2)}{2} + V2}{2} \times \frac{\left((X3 - X2) \times \frac{(Y3 + 3Y2)}{2} \right)}{4}$$

This method of flow calculation is considered the most accurate, and differs slightly from the methods used in RHABSIM, PHABSIM and RHYHABSIM. For this reason, flows calculated in SEFA may not be exactly the same as in the other programs and predicted velocities will also be slightly different.

Flows calculated at each cross-section should be examined closely as excessive variation could indicate data errors. Usually flows at individual cross-sections should not be more than 10% different from the mean. If they are, and this is not due to data errors, it may be because the flow was not at right angles to the section with the result that the flow is overestimated. If this occurs, the offset spacing should be adjusted by multiplying by the cosine of the current angle.

Another explanation for large variations in measured flow is that cross-section locations are not ideal sections for measuring flow. Measurements in pools are often inaccurate, but accuracy can be improved by taking measurements at 0.2 and 0.8 of the depth.

9.3 Plotting cross-sections

Plotting the cross-sections is advisable to check that data points have been entered correctly.

Each cross-section can be displayed, as either water depth or elevation plotted against offset.

The default is to plot depths, but elevations can be plotted by specifying elevations in the graph options.

The waterway area is shaded blue and, if velocities are measured, they are plotted in yellow to a reverse scale above the water level. The default plotting scale may differ between sections but can be held constant by “fixing scale” in the graph options.

Velocity is shown as a dashed line and ground profile as the solid line. Measurement points are indicated by triangles on the ground and velocity lines.

The SZF is shown as a black line on the cross-section plot. If not wanted in the display, uncheck SZF in the graph options (see printing and copying).

Cross-sections can be compared by plotting in multiple windows and setting the same global scale for each window.

10 Survey information and export

10.1 Reporting

Three types of report can be produced under the Hydraulic Habitat/Reports.

Statistics

This lists as text details of the survey, such as the total number of measuring points in and out of water and their average spacing.

Calibration

This produces a detailed report on the survey calibration.

Summary

This produces a detailed report on the survey. It lists details of the survey along with any comments.

10.2 Export SEFA file

Data saved in the *rhbx* file can be exported as ASCII text files; the reverse procedure used for import. Use the File->Export menu with file type Survey as tab delimited text file (*.**hab**).

Hab file export also creates other files (*.con and *.vdf) that contain calibration data. (

The order of data in a text data file is similar to the order used in the field. The text file format is useful because it can be read or written by any text editor or word processor.

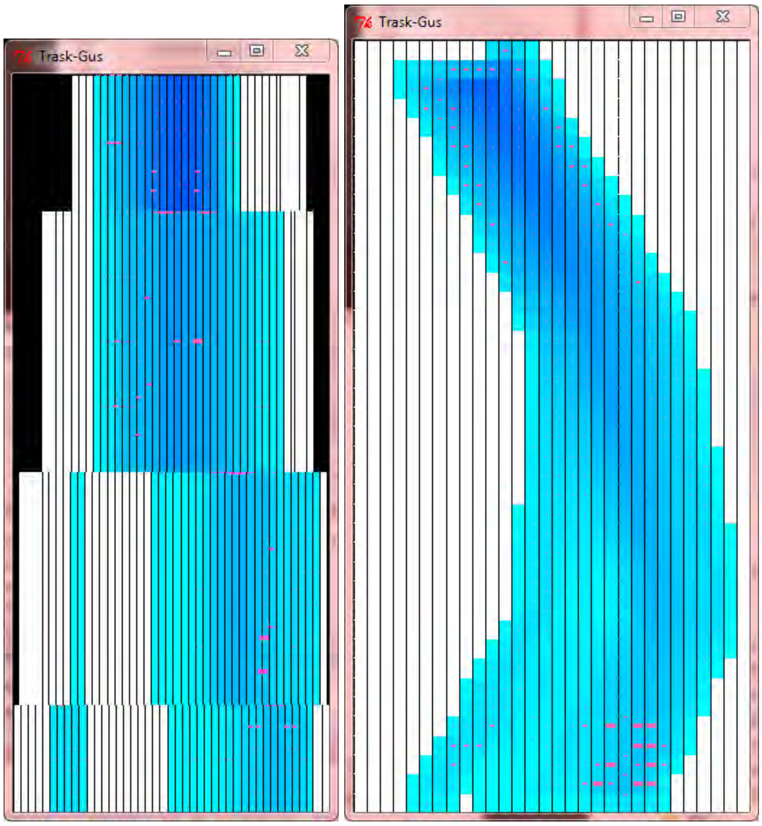
Numerical data are separated by one or more blanks or tabs.

10.3 Export inSTREAM data files

Two files are exported for inStream; one containing the geometry of the cells and the other containing the predicted depth and velocity in each cell for the range of flows specified. Subscripts are added to the filename specified "_CellGeometry.dat" for the geometry data and "_HydraulicData.csv" for the hydraulic data.

Use the File->Export menu with file type inSTREAM files (*.csv and*.dat).

The definition of the data exported will depend on whether the reach is a representative reach or habitat mapped, as shown below.



Example of inSTREAM output for habitat mapped reach (left) and representative reach (right).

11 Habitat suitability curves

The HSC menu item View Suitability Curves will import habitat suitability curves from a library file, display HSC that are in a library file. The menu item Select Suitability Curves is enabled when a rhbx file is open and allows the selection of habitat suitability curves from a library file for use in subsequent habitat analyses. The selected curves are stored in the file that is open, so that a rhbx file must be open before HSC can be selected.

The first step of habitat modeling is to select the suitability curves for the species that you want to model. Click 'Model', 'Select suitability curves', and you should see a list of suitability curves that are in the library file. These criteria describe the variation of the suitability index (an index varying between 0 and 1) with the habitat variable (e.g., depth, velocity etc.). If no files are shown, they must be imported by clicking the Import button and selecting a file (*.prf, *.xls*, *.rcv) containing the curves. The format of the text files is described in “Habitat suitability file import”.

Select a curve by clicking on the arrow and it will appear to the left under 'Selected curves'. Double-click on the species name to see the curves plotted. The suitability curves are held in a SEFA HSC library file (*.lib which is a non-ASCII file). Other suitability curves can be added to the library by editing the *.prf or *.xls* file and re-importing to replace the existing library file. It is good practice to add the reference to the source of the suitability curve, e.g. suitability curves for different life stages of brown and rainbow trout from U.S. (Bovee, 1978; Raleigh et al., 1984a and b; Raleigh et al., 1986) and New Zealand for NZ trout and native fish sources (Hayes & Jowett, 1994; Jowett & Richardson 2008; Shirvell & Dungey, 1983), and suitability criteria for food (benthic invertebrate) production (Waters, 1976).

Warning: Habitat suitability criteria are the most important part of habitat modeling and have more influence on results than any other part of the procedure. Thus, it is important that the suitability criteria are appropriate; otherwise the results will be erroneous.

Before AWS can be evaluated, a library of habitat suitability criteria (HSC) must be set up. This is done by importing data from a file (*.prf or *.xls*, *.rcv).

To import a set of habitat suitability curves, you must first open or import some cross-section data. When this is done, the habitat suitability icon  and HSC>>Select suitability curves menu item are enabled. Click on the icon or select the menu item to display the contents of the current HSC library (*.LIB). Press the Import button to select the file containing the curves. You can then choose to replace the existing curves, merge the new curves with the existing curves or save with a different library name.

Press the Select library button to select a different habitat suitability library file.

Habitat suitability curves can be selected (or de-selected) from this library and applied in any habitat analysis.

Habitat suitability curves in either the library or selected list can be displayed by double clicking on any item in the lists.

The selected suitability curves are contained in the rhbx file. This information is overwritten each time a new set of suitability curves is selected.

The substrate habitat suitability curve describes the suitability of each substrate category. If using the SEFA substrate categories, substrate habitat suitability is calculated from the percentage of each of those substrate categories. The substrate suitability at measurement point is the sum of the suitability for each category multiplied by the percentage of that substrate category at the point.

11.1 Use specified habitat suitability

The default suitability curve names are **DEP**TH, **VEL**OCITY, and **SUB**STRATE as in the example below:

Shortfin eel < 300mm //Jowett & Richardson 2008

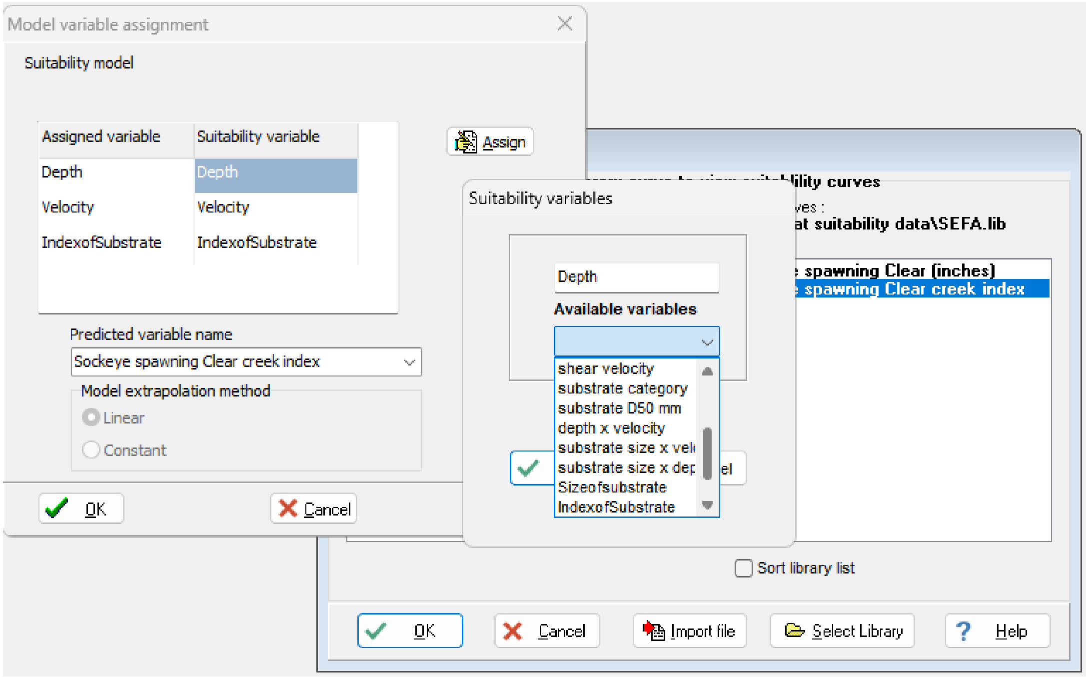
Depth	0	0.08	0.16	0.25	0.38	0.6		
Weight	0	0.84	1	1	0.91	0		
Velocity	0	0.03	0.05	0.4	0.6	0.8	0.9	1
Weight	0	0.95	1	1	0.6	0.3	0.15	0
Substrate	1	2	3	4	5	6	7	8
Weight	1	1	0.6	0.5	0.5	1	1	0.82
Cover	0	2	3	4	5	6	7	8
Weight	0	1	0.6	0.5	0.5	1	1	0.82

end

The default names are recognized and are associated with calculated depth, velocity and substrate composition.

However, suitability curves for user specified variables can be specified for other hydraulic variables or attributes as listed below. When a suitability curve is selected for a rhbx file, any non-default curve name, the attribute names in the file are examined. If the attribute name is the same as the curve name then that attribute is associated with that curve and weights are applied as for the other curves. For example, if the rbhx file contained an attribute named “cover” specifying a cover grade at each point and the suitability curves shown above were selected, the cover attribute would be automatically associated with the cover suitability curve.

When a curve is selected for use in the file and it contains a user specified variable that is not automatically recognised, the variable must be associated with an attribute or set of calculated hydraulic variables, using the dialogs shown below.



The set of calculated hydraulic variables that can be associated with user specified variables are:

Depth

Velocity

Velocity/Depth

Pool

Run

Riffle

Shear velocity

Substrate index[3]

Substrate D50 mm

Depth x velocity

Substrate index x velocity

Substrate index x depth

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[3] This index is the weighted sum of the eight substrate categories and varies between 1 and 8.

Attributes

12 Model Calibration

The calibration menu contains the calibration procedures for:

- survey flow
- velocity distribution factors
- ratings

Models are automatically calibrated when imported or entered. However, it may be necessary to fine-tune these calibrations.

Even, if models are not re-calibrated the default calibration should be checked to ensure data integrity. This is especially necessary for models with multiple channels.

12.1 Flows and survey flow

12.1.1 Measured flow

The flow at each cross-section is calculated from offsets, depths and water velocity. This flow is known as the measured flow for a section.

12.1.2 Survey flow

The best estimate of the flow at which the survey was made is known as the survey flow. This flow may also be termed the calibration flow or best flow.

The default survey flow is the average of all measured flows.

If the reach contains cross-sections with multiple channels, the survey flow of each channel is the best estimate of the flow in individual channels. This means that the survey flow varies between cross-sections. Therefore, the “Vary flow between sections” check box must be checked.

Calibrations of stage-discharge relationships, velocity distribution factors (VDFs), and friction losses for water surface profile modeling are all based on the calibration flow. The average flow is usually the best measure of the calibration flow because most surveys are made at one flow and in a section of river where there are no significant tributary contributions or flow losses. However, the average flow will sometimes be influenced by large errors in flow measurements at some cross-sections. The survey flow can be adjusted by omitting particular sections or set to the flow at one section that is considered an accurate measurement.

Double clicking on any of the measured flows, either the mean or any of the cross-section flows, will set the survey flow to that value.

Varying flows between cross-sections

If the flow varied during the time of the survey or there were significant tributary contribution, the Vary flows between sections checkbox should be ticked and a survey flow can be specified for each cross-section.

If the survey flow is changed, the reach will be re-calibrated (ratings, velocity distribution).

If flows are to be varied between cross sections for predictions, there are two options. Either divide the reach up into smaller reaches each with the same flow or analyse as a single reach.

Single reach with varying flows

To vary flows in a single reach requires setting the flow to be modeled for each cross-section by checking the Vary flow between sections checkbox.

When you do this each reach is modeled for the flows you have specified. The critical thing is the number of calculation steps should be the same (SEFA won't allow otherwise). This is because the AWS and other variables are summed over all cross sections for each flow step.

The procedure would be to decide on a flow range and interval for the section with the lowest flow range i.e. section 0 (usually the most upstream section and the first in the data) - let's say the flow range is 0 to 500 at intervals of 50. This would give 10 steps (500-0)/50.

Then for sections where the flow will be higher section n, decide on the flow at the section that would occur when the flow at section 0 is 0 - let's say 55. Then decide on the flow that would occur when section 0 is at its maximum value of 500 - let's say it would be 655. Then specify the interval so the number of steps is the same as in Section 0 i.e. (655-55)/10 or 60.

The first step would calculate AWS for section 0 at 0 flow and then AWS for section n with a flow of 55 and add them together. The second step would add AWS for section 0 at a flow of 10 with AWS at section n for a flow of 115 etc.

Section 0 is the reference flow and the flows in the output refer to the flow at that section. If Section 0 is not the first then the output flows would refer to the first flow in the reach.

Multiple reaches with same flow at each cross-section

To model as multiple reaches, you would set the flow range to be modeled for the reach (with "vary flow between sections" unchecked).

The first reach would usually be the most upstream reach and the flow in this reach acts as the reference flow.

The first reach might model flows of 0 to 500 at intervals of 50.

Next click on the Reach button (top right) and specify the flow range for this reach in the same way as above - i.e. with the same number of steps as in the first reach (55 to 655 at intervals of 60).

12.1.3 Velocity distribution across cross-sections

The velocity distribution factors (VDFs or Manning N values) define the transverse distribution of velocities across a cross-section. VDFs are used to calculate velocities at flows other than the survey flow and are assumed to be constant with flow. To see the values, click 'Edit velocity distribution factors'.

Usually, the VDF values vary around 1. The value should be close to 1 for all segments, if the velocity is distributed uniformly. However, you can see from the plots that the value usually reduces near the banks, and that the variation is largest in riffles because of the variation in roughness and velocity in the shallow flow across the channel. VDFs can only be calculated for points in the wetted cross-section. Points outside the wetted cross-section (marked by black) are given values equal to the nearest wetted point. Thus, it is better to collect velocity data (i.e., to carry out a survey) at a high flow and predict velocities at lower flows than vice versa.

The values of VDFs at points that were dry when the cross-section was surveyed and will become wetted at higher flows (black points) can be edited. Editing VDFs is done easily in SEFA by clicking and dragging the points on the lower half of the 'Edit velocity distribution factors' plots. This is especially necessary when points that were dry at the survey flow by default are given very high values. Observations in the field (boulders, plants, etc.) are helpful here. The original values calculated by the program can be obtained at any time by clicking 'Reset velocity distribution factors'.

The modeled velocity distribution at different flows can be viewed under 'Model', 'Velocity distribution'. Try pressing Shift F2 to see what the velocities would be if VDF were equal to 1 at all points ('VDFs not applied'). Press F2 again to return to the measured velocities ('VDFs applied'). Press Shift F1 to obtain the velocities for what is referred to as 'Best VDFs' (meaning 'Best guess of VDFs'). 'Best VDFs' have values equal to the ones calculated from the survey flow at lower flows, values of 1 at higher flows, and in-between values for intermediate flows (the exact criteria are described in 'Help' under 'Velocity distribution factors'). The effect of varying VDFs as described above on the modeled habitat compared to the results using constant VDFs can be seen by clicking 'Model', 'VDF sensitivity analysis'.

12.2 Calculation options

Methods for calculating hydraulic habitat can be changed in the menu File>>Preference>>Calculation.

The default methods are recommended for general use, but preferences can be set to allow an emulation of IFG4 Manning's N calibration and calculation of velocity.

12.2.1 Rating curve method

Log-log rating relationships are derived for stage-discharge pairs of measurements. The default method is to fit the curve through the survey flow and the best least square fit to other stage-discharge pairs. This method is most appropriate if the survey cross-section is based on measured water depths, because it does not introduce spurious depth errors in depth when predicting water levels at the survey flow.

The alternative method is that used in IFG4 (PHABSIM) to fit the curve through all stage-discharge pairs. This is most appropriate if bed levels rather than water depths were measured at the survey flow,

12.2.2 Velocity prediction method

The default velocity calibration and prediction method is to calculate Manning's N and VDF from conveyance (a function of hydraulic radius) at measurement points. When predicting velocities for a given flow, they are calculated from conveyance and are then adjusted so that the they give the given flow times the ratio of measured to survey flow. Using this default method and the default log-log rating method predicted velocities at the survey flow will be the same as measured velocities.

The alternative method is that used in IFG4 (PHABSIM), where Manning's N values are calculated from water depth at each measurement point and the slope for the cross-section (usually the default slope of 0.0025). When predicting velocities for a given flow, they are calculated using Manning's equation (N, depth and slope), with the velocities are then adjusted so that the they give the given flow.

12.2.3 Habitat calculations

Calculation of habitat suitability. Three methods of calculating the combined habitat suitability index (CSI) are available. The default is for CSI values to be multiplied to form a single combined index (multiplication of individual suitabilities). The geometric mean of individual suitabilities and the minimum of individual suitabilities are the other choices.

12.2.4 Interpolate habitat between measurement points

When the Interpolate habitat between measurement points check box is checked, habitat suitability is calculated at the measurement points and at 10 linearly interpolated points between measurements. This is the default method and SEFA calculates habitat suitability by interpolating linearly at between cross-section measurements points. For example, if one point is measured at the water's edge and the next in the water at a depth of 0.5 m, the program will calculate habitat suitability at 0.025 m increments from 0 to 0.5 m,

If Interpolate habitat between measurement points is not checked, the PHABSIM method is used and habitat suitability will be calculated at each measurement point and that value is assumed to apply between the mid-points of adjacent measurement points (i.e., a cell).

12.2.5 Cross-section extrapolation

When a water level is higher than the left or right bank, the water edge is estimated by linear extrapolation. However, if the bank slope is less than 0.05 (the default), a vertical bank is created. PHABSIM always creates vertical banks at the edge points of a cross-section.

12.2.6 Hydraulic rating roughness

Stage discharge relationships calculated using Manning's equation (MANSQ) assume that hydraulic roughness varies with discharge. The default method is to allow roughness to vary with flow. This choice usually has little effect on rating curves.

12.2.7 Conveyance for WSP

When calculating a water surface profile, the conveyance can be calculated in two ways. A combination of Harmonic and arithmetic mean is the default method. This rarely has much effect on water surface profiles.

13 Rating curves

A rating curve is the relationship between water level and flow in a river. In a river or lake, the water level is “controlled” or “held up” by a downstream feature or features. These features are known as hydraulic controls and can be weir-like features such as riffles, constrictions in the channel, or friction with the stream bed. At low flows, the hydraulic control is usually local and may take the form of a riffle at the end of a pool, the friction generated by the substrate of a riffle, or a combination of hydraulic controls. As the flow increases the local controls can be “drowned’ and the hydraulic control is from features further downstream, such as channel friction.

13.1 Hydraulic theory of rating curves

In SEFA, the SZF rating curve is:

$Q = a(H\text{-}SZF)^{exp}$

Where *Q* is the flow, *H* the water level, *SZF* the stage at zero flow, and *exp* and *a* are constants.

The constants *a* and *exp* depend on the type of hydraulic control and how the width (*W*) varies with flow. For example, a riffle control at the tail of the pool acts like a broad crested weir according to the equation

$Q = 1.7\ W\ (H\text{-}SZF)^{1.5}$

The width is the width of the hydraulic control and this can be different from the width of the cross-section to which the rating is applied.

At-a-station hydraulic geometry[4] for New Zealand rivers gives the relationship between width and flow as:

$W = 15.8\ Q^{0.176}$

So that $Q = 54.24\ (H\text{-}SZF)^{1.82}$

For friction control, Mannings equation applies and:

$Q/(\ W\ (H\text{-}SZF)) = ((H\text{-}SZF)^{2/3}\ S^{1/2})/N$

$Q/(\ 15.8\ Q^{0.176}\ (H\text{-}SZF)) = ((H\text{-}SZF)^{2/3}\ S^{1/2})/N$

So that with a constant N of 0.035 and slope of 0.0025, $Q = 43.92\ (H\text{-}SZF)^{2.02}$

[4] Jowett, I.G. (1998). Hydraulic geometry of New Zealand rivers and its use as a preliminary method of habitat assessment. Regulated Rivers 14: 451-466.

In rivers, the rating curve exponent usually varies between 2 and 5. This means that width may increasing with flow more than predicted from the hydraulic geometry and/or Mannings N changes with flow.

The rating curve equation usually fits measured gauging well over a certain range of flows. Consideration of the hydraulics suggests that the exponent and constant could change with flow. For example, at high flows the water level may overtop the confining banks and the width would begin to increase more rapidly than in the confined channel. Similarly, Mannings N might decrease with flow at low flows but increase with flow at high flows. Such situations can be handled by having low flow and high flow rating curves. The hydraulic rating in SEFA can sometimes[5] predict water levels at high flows more accurately than the SZF rating because it is calculated from the cross-section.

13.2 Rating curve methods

Rating curves are automatically fitted to the gaugings for each cross-section by 3 methods when either importing a file or entering new cross-section data.

The procedure is to:

1. examine the alternative rating curves (Display section ratings menu item)

2. compare the shape of the ratings between sections (Display/Edit all ratings menu item)

3. select (Select ratings menu item) one rating to be used in calculating water levels at a cross-section.

A concise summary of the rating curve equations can be obtained using the recalculate menu. The reCalculate menu item recalculates rating curves, resetting any equation parameters that have been set by editing the equations. A summary of the rating curve equations is shown for each method. The correlation coefficients indicate the goodness of fit to the points. Rating curves can be compared either in tabular form or graphically to determine which curve is best to use for extrapolation to other flows. Parameters can be altered to get a better fit or if data errors are suspected.

The ratings can be displayed for each cross-section on a normal or logarithmic scale. The stage can by plotted either as the height above SZF or as elevation.

The default option is for every rating to be fitted through the survey flow and its associated water level with the best least squares fit to the calibration gaugings. If the calculation option to fit ratings through the survey flow and calibration gauging is used the rating will be a least squares fit through the survey flow and gauging and this will not necessarily be through the survey flow.

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[5] The prediction should be better only if the cross-section is similar to the cross-section of the hydraulic control.

Least squares fits are calculated as geometric means of coefficients derived in both directions (x on y and y on x). This is considered a better solution than minimizing the stage deviations, because there are probably errors in both stage and discharge.

The critical flow rating is shown as a check on other ratings. Rating curves are calculated by 4 methods.

1. Log-log least squares fit through points and SZF (SZF is either the section minimum or a specified value)

   Flow = a * (Stage-SZF)^b

2. Log-log least squares fit through points with SZF adjusted so that the correlation coefficient (r) is a maximum. This is the "best-fit" rating curve.

3. Hydraulic method (MANSQ) using Manning's *n* is calculated for each gauging:

   *Flow = 1/n * A * R^2/3 * S^1/2*

   assuming that the slope is constant. The variation of Manning N with flow is calculated according to the equation:

   *n = a*Flow^beta*, or

   n = a(Hydraulic radius – hydraulic radius at SZF)^beta*, depending on the setting in calculation preferences. When the hydraulic method is used in pools (Fr < 0.18 at calibration flow) the hydraulic radius (R) and cross-section area are reduced by the hydraulic radius and area at the SZF. When the Fr is greater than 0.18 no adjustment is made for the SZF.

   Usually Manning's *n* increases as flow decreases so that beta is negative.

4. Log-log least squares fit through stage of zero flow and water surface levels calculated by water surface profile modeling. This is fitted only if water surface profiles have been modeled.

Stage discharge curves do not necessarily follow a log-log line through the stage at zero flow. Cross-section geometry can be such that the exponent changes when the flow range changes. In some situations, the best fit with adjusted SZF might be more appropriate.

Rating curves are derived so that the derived equation plots through the calibration flow and water level. The procedure is to minimize the sum of the squared departures of data about a line (y = ax+b) passing through the calibration stage (y') and discharge (x').

$S = \Sigma(y_1 - y' - a(x_1 - x'))^2$

where S = sum of squares of deviations from the line through y' and x'.

Minimizing the sum of the squares:

$\partial S/\partial a = 0 = \Sigma(x_1 - x')y_1 - y'\Sigma(x_1\text{-}x') - a\Sigma(x_1 - x')^2$

$a = (\Sigma(x_1 - x')y_1 - y'\Sigma(x_1\text{-}x'))/(\Sigma(x_1 - x')^2)$

$b = y' - ax'$

Because the gaugings can contain errors in both stage and discharge, the regression lines were calculated for both x on y and y on x and the geometric mean coefficients calculated. Geometric regression has been shown to be a robust method of minimizing the deviations from a regression line in both the x and y directions. A similar procedure was followed when finding the SZF of that produced the best fit, by allowing the stage for zero flow vary between the minimum gauging level and a point somewhat below the minimum section level (half the distance between the minimum gauging level and the minimum section level). If this rating curve is used, it is possible, for very low flows, to calculate a stage that is lower than the section minimum. Thus, the adjusted SZF will always give a better fit to the gaugings but might give incorrect stages when extrapolated to very low discharges. The plotted curves can be examined to determine if this is likely to occur.

The default method of deriving log-log rating relationships is to fit the curve through the survey flow and the best least square fit to other stage-discharge pairs. This method is most appropriate if the survey cross-section is based on measured water depths, because it does not introduce spurious depth errors in depth when predicting water levels at the survey flow.

The alternative method is to fit the curve through all stage-discharge pairs. This is most appropriate if bed levels rather than water depths were measured at the survey flow. This is only method used in PHABSIM.

13.2.1 Rating Curve Displays

The rating curves for all cross-sections are viewed individually by clicking 'Display section ratings' and all on the same plot by clicking Hydraulic calibration>>Ratings>>Display all ratings. Double-click on the plot to get to 'Options'. Three ratings are displayed on the section plots: (1) SZF rating, (2) Best SZF rating, and (3) Hydraulic rating. Both rating curve types (1) and (2) use a form of least squares estimation to fit the equation

Q = a(H – SZF)b

to data (a straight line on a plot of log(H-SZF) versus log(Q)). Note that all curves go through the flow and the water level measured during the survey. This is done in order to achieve that, when the survey flow is modeled, the rating curves will predict the water level and consequently the predicted depths and velocities identical to those measured. (This is a small departure from the procedures used in PHABSIM where predicted depths and velocities are not exactly the same as those measured).

Rating curve type (1), '*SZF* rating', uses least square estimates of a and b and the measured value of *SZF*, while rating curve type (2), 'Best SZF rating' (meaning 'SZF that gives the best fit to gaugings), uses least squares estimates of a, b and a value of *SZF* that gives the best fit of the points to the curve. Thus, the value of *SZF* in (2) is allowed to deviate from the measured value, see for example Section 1 where the estimated value of *SZF* in (2) is -0.639 m and different from the measured value of -0.481 m in (1). Rating curve type (2) was included because it can be difficult to measure the *SZF* correctly in the field and/or rating curve (1) is not necessarily applicable over all ranges of water level. Rating curve type (3) is based on Manning's formula with the water depth set equal to the water level minus *SZF*. Manning's N is allowed to vary with flow (see how it varies by clicking 'Variation of Manning's N' under 'Options').

The menu Hydraulic calibration>>Ratings>>Display all ratings plots the ratings curves for all cross-sections on the same plot. This is a good way to see whether some of the ratings deviate considerably from the others. The type of rating curve ('SZF rating', 'Best SZF raring' or 'Hydraulic rating') to be plotted is selected on the 'Options' dialogue (double-click on the plot to get to this, or click 'Graph', 'Options'). The 'Edit' button on these three plots allows you to change the exponents of the rating curves, if needed. The preferred type of rating curve is selected using the last of the three menus under 'Calibration, the 'Select ratings'. Rating curve type (1) is the default option. In cases where there are enough flow gaugings covering a wide range of flows, all rating curves are usually well defined and follow the same path (use the 'Display section ratings' to compare the different types of curves) and any of the rating curves can be used. In difficult cases, the exponent for types (1) and (2) should lie in the range 1.5-4.5. All the selected rating curves for the reach can be viewed together by clicking 'Display all ratings' and choosing 'Show selected ratings' from the 'Options' dialogue.

Rating curves can be edited (arbitrarily) using Hydraulic calibration>>Ratings>>Edit rating exponents. The exponent of the log-log ratings, the beta value of the hydraulic ratings and exponent of the log-log WSP ratings are displayed and can be changed.

When the rating curves, (H-SZF) versus flow, for each cross-section are plotted to a logarithmic scale on one graph, the rating curves will form a pattern where no rating curve crosses any other rating curve if the cross-sections have the same exponent (slope).

If the rating curve levels are to a common datum (e.g. sea level) then the ratings should plot with the downstream cross-section rating will be the lowest on the graph with the next cross-section rating above it etc. The ratings should not cross each other because this would mean that water was flowing uphill.

However, if the rating levels are not to a common datum, it is possible that they cross because the hydraulic controls vary from cross-section to cross-section and the exponents (slope of rating) will differ.

13.3 Rating selection: Select rating menu

Ratings used for the prediction of water level from flow can be selected in the Hydraulic Calibration>>Ratings>>Select Ratings menu item.

Gaugings often tend to be more linear than the curve of log-log fit through the SZF would suggest. Ideally, the ratings by all 4 methods are so close that the choice doesn't matter. The SZF that is used in a rating can be altered directly. The value of beta in Manning's *n* ratings can also be altered.

The log-log least squares fit through the section minimum or stage of zero flow is the default rating and generally appropriate and robust.

However, any of the available rating curves can be selected (Hydraulic calibration>>Ratings>>Select ratings menu item) and used for prediction of water levels.

13.4 Critical flow rating

The critical flow rating is the stage/discharge relationship that would exist if the section were a critical control, i.e. the water level at the section was not influenced by downstream conditions. Critical flow across a whole section of the river is very unusual in natural rivers, so one does not expect a rating curve to cross the critical curve. Any rating curve that crosses the critical flow rating is probably incorrect, at least in the region where it crosses and usually a rating will be parallel to the critical flow rating. The height of the curve above the critical flow rating depends on how close to critical the flow is. For a swift riffle, it will be close, for a slow run it may be well above the critical rating, possibly out of sight on the plot.

13.5 Comparing and editing rating curves

The shape of ratings for all cross-sections can be compared using the Hydraulic calibration>>Ratings>>Display all ratings menu option. Generally, ratings within a section of river are similar and are either parallel to each other or form a pattern.

Ratings can be edited by pressing the edit button. Rating exponents for all ratings will be displayed so that their values can be compared, and the exponent for any rating can be changed. The modified rating is then plotted on the curve, so that you can see the change.

Any rating that crosses other ratings is suspect, but not necessarily wrong.

In addition to the graphical comparison of ratings, the check procedure produces a table that can be used to check the consistency of flows and water levels between sections.

This table lists the survey flow and calibration flows in m^3/s or cfs, along with the flow change in L/s per mm (or in feet units) change in water level between the calibration flow and water level and the survey flow and water level.

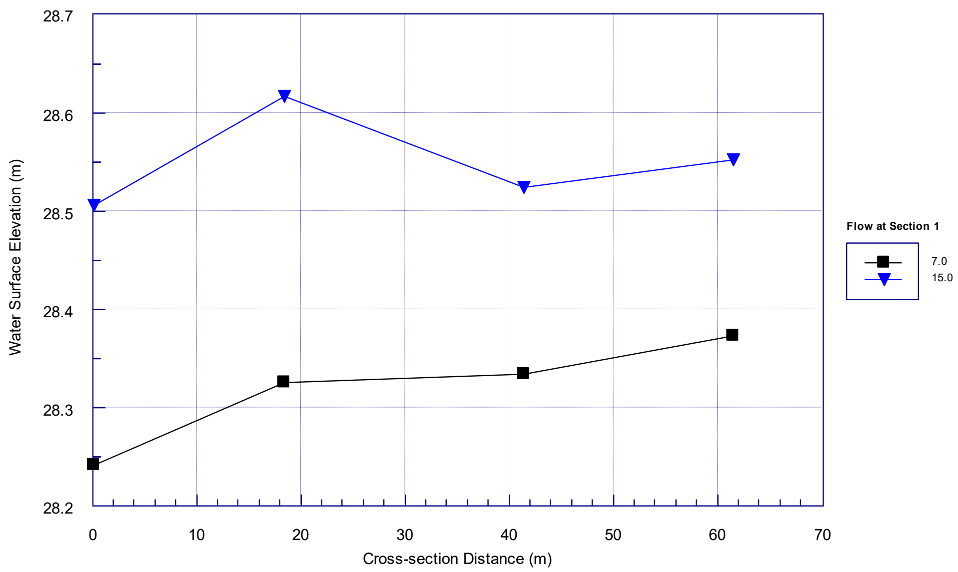
Flow change/mm = (Survey flow - Calibration flow)/(Survey water level- Calibration water level)*1000

Usually, the flow change for unit change in water level is reasonably consistent from cross-section to cross-section. Large departures from the mean indicate the possibility of an error.

13.6 Prediction of Water Surface Elevation

Water Surface Elevations are predicted from flow using rating curves selected in the Hydraulic Calibration>>Ratings>>Select Ratings menu item, as described in 13.2.

The water surface profile for the modeled flows can be plotted with the Hydraulic Calibration>>Water Level Predictions menu item. This is particularly useful for checking rating curves. If the water levels are all referenced to the same datum, are reasonably close together, and the cross-sections are in either upstream or downstream order, the water level at each downstream section should be less than that at each upstream section (i.e., water flowing downhill). Even if levels are not referenced to the same datum, there should usually be a similar change in water level with flow at each cross-section. For example, in the test dataset, water levels were referenced to the same datum and ratings were fitted to the calibration gaugings. At the survey flow of about 7 m^3/s, the water level increases with distance upstream at each cross-section. However at a flow of 15 m^3/s, the predicted water level at section 2 is too high and the water flows “uphill” from section 3 to section 2.



13.7 Extrapolation of rating curves

Bob Milhous examined flow gauging records to determine how far rating curves should be extrapolated. He suggested that you don't extrapolate a rating curve beyond 2.5 times the highest data point or below 0.5 times the lowest. Although this provides some guidance, there is no general rule. It depends on the site characteristics and more importantly the stage at which you have taken the flow measurements. If the measurements are at high flows then extrapolation to more than 2.5 the highest might be valid because the relationship is essentially linear, but extrapolation to 0.5 the lowest might be doubtful because of the curvature in the rating at low flows. Vice-versa if the flow measurements are at low flows.

The critical flow rating curve and the overall picture created by all the rating curves on a river can be used to assess the quality of the rating curves. The critical rating is particularly important for assessing whether extrapolations are reasonable. Rating curves in runs and riffles should be "parallel" to the critical rating. They should not cross the critical rating (meaning supercritical flow which is extremely unlikely in natural channels). Riffles can certainly tend towards critical and even reach it at low flows.

Once you have checked that the ratings look reasonable with respect to the critical rating, you check that all the ratings have similar log-log slopes. If the ratings (cross-section water levels) are referenced to a common datum, you can check that predicted water levels always decrease with distance downstream. This is a very good check on rating curves. SEFA has a menu option Hydraulic Calibration>>Water Level Predictions that does this.

14 Velocity distribution factors

Velocity distribution factors or Manning N values are calculated from the velocities that were measured across each cross-section and the survey flow. Velocity distribution factors, ratios of actual measured velocities to calculated velocities, or Manning N values (depending on selected preferences) are fitted automatically.

When simulating flows, calculated water velocities are multiplied by the velocity distribution factor to give a simulated water velocity. This will reproduce the measured velocity distribution when the measured flow is simulated.

Simulated velocities will always be zero at points with zero velocity distribution factors.

Usually velocity distribution factors vary across a section in a regular pattern. Adjustments to points should attempt to emulate this pattern. Good field notes can aid the estimation of VDFs at and above stream banks. Obstacles to flow, such as vegetation or large boulders upstream, should be noted and estimated VDFs reduced accordingly.

14.1 Calculation of Velocity Distribution Factors and N values

Manning's equation

Manning's equation is a relationship between the mean velocity (V) in a channel, the slope (S) of the channel, and hydraulic radius (R) of the channel, with manning's N as a constant (although it does *vary with flow).*

$$V = 1/N \times R^{2/3} \times S^{1/2}$$

$$N = 1/V \times R^{2/3} \times S^{1/2}$$

IFG4 emulation

In IFG4, Manning's N is calculated from the depth (D) and velocity (V) at a point rather than the hydraulic radius, i.e.,

$$N = 1/V \times D^{(2/3\text{-}beta)} \times S^{1/2}$$

When the flow changes, a new Manning's N (N_{new}) and a new velocity (V_{new}) are predicted for the new depth (D_{new}):

$$N_{new} = N \times (D_{new}^{\ beta})$$

$$V_{new} = 1/N_{new} \times D_{new}^{\ 2/3} * S^{1/2}$$

The constant beta describes the way in which Manning's N changes with discharge. It applies to the point measurements across the cross-section. In general, roughness increases as the depth becomes shallower so that beta usually has a value of zero or less.

SEFA default method

In SEFA, velocities are calculated using conveyance and manning's equation.

The conveyance of a cross-section is:

$$Q = K \times S^{½}$$

where Q is the flow, S the slope, and K the conveyance.

Using Manning's equation, the conveyance K becomes:

$K = (A \times R^{2/3})/N$, where N is Mannings N, A cross-section area, and R the hydraulic radius

For any cell in the section, the ratio of cell flow Q_1 to cell conveyance is equal to the total section flow Q divided by the total section conveyance (Henderson 1966 "Open channel flow" p. 145)

$$Q_1/K_1 = Q_2/K_2 = \Sigma Q/\Sigma K$$

The velocity in a cell can be calculated from the above relationship and $V_1 = Q_1/A_1$:

$$V_1 = R_1^{(2/3\text{-beta})}/N_1 \times Q/K$$

where Q = total flow, K total conveyance, R_1 cell hydraulic radius, N_1 cell roughness.

The velocity distribution factor (VDF) or cell Manning's N (N_1) is a measure of how cell roughness varies across a section.

$$V_1 = R_1^{(2/3\text{-beta})}/N_1 \times Q/K = R_1^{(2/3\text{-beta})}/N_1 \times S^{½}$$

becomes

$$V_1 = R_1^{(2/3\text{-beta})}/N_1 \times (QN)/(AR^{2/3})$$

Where N is the section roughness, A section area, and R section hydraulic radius.

If Manning's N is uniform across the section then the velocity across the section varies as $R_1^{(2/3\text{-beta})}$, if N is not constant then the velocity varies with cell roughness times $R_1^{(2/3\text{-beta})}$. The velocity distribution factor is defined as the ratio of the measured velocity to the velocity that would be predicted assuming that the section N applies across all cells:

Assuming $N_1 = N$, the predicted velocity at 1 is $V = R_1^{(2/3\text{-beta})} \times Q/(AR^{2/3})$

VDF = V_1/V where *V* is the predicted velocity at 1 assuming constant N across section and V_1 the measured velocity, and *VDF* = N/N_1.

The velocity at point i V_i can be predicted by:

$V_i = VDF_i \times R_i^{(2/3\text{-beta})} \times (Q/AR^{2/3})$

Where VDF_i is the VDF for point i and *Q,A,R* the cross-section properties at flow *Q.*

This formulation is similar to that used in IFG4 in PHABSIM and RHABSIM except they use depth at a point instead of cell hydraulic radius and values of N_1 instead of the N ratio (VDF).

14.2 Velocity prediction and velocity adjustment factor

When velocities and depths are predicted for the modeled flow across a cross-section using the methods outlined above, the discharge that is calculated using the VDF (N) values will be slightly different from the modeled flow. The velocities are all then proportionally adjusted so that the discharge calculated from the predicted depths and velocities matches the modeled flow. The value by which the velocities are adjusted is known as the velocity adjustment factor or VAF.

The default adjustment to the modeled discharge is different in SEFA to that in IFG4, although there is an option to use the IFG4 method. IFG4 adjusts velocities so that they equal the modeled discharge, whereas SEFA adjusts velocities so that they equal the modeled discharge times the measured discharge divided by the survey flow.

The survey discharge is the best estimate of the flow at the cross-section when the survey was carried out and the measured discharge is the discharge calculated from the measurements of offset, depth and velocity.

Advantages of SEFA method

The velocities across a cross-section are rarely controlled solely by roughness, and area result of upstream obstacles to flow such as boulders etc., so that the concept of velocity distribution factors rather than roughness factors is more sensible. Where a measured velocity is zero, the VDF will be zero whereas Manning’s N will be undefined.

Across a cross-section the “average” value of the VDF will be about 1, and that means that the velocity that was measured equals that predicted by the conveyance relationship. If a VDF is higher than 1 then the measured velocity is higher than that predicted by the conveyance relationship, i.e., if the VDF is 2, the measured velocity is twice that predicted from the conveyance relationship. Manning’s N values vary according to the slope of the cross-section and it is difficult to determine where the roughness is higher than the average section roughness and where it is lower. Manning’s N values calculated from depths at a point will be more variable than Manning’s N or VDFs calculated from the cell hydraulic radius. The velocity at a point is controlled not only by the depth at the point, but also by the depths adjacent to that point, so a Manning N or VDF based on cell hydraulic radius is conceptually more realistic. However in practice, there is very little difference between predictions made using Manning's N calculated according the IFG4 formulation and predictions made using VDFs calculated with the SEFA formulation, if the same method of velocity adjustment is used, and it is simply a matter of preference which is used.

More importantly the default velocity adjustment in SEFA is different to that in IFG4, and this negates the IFG4 restrictions that require cross-sections to be at right angles to the flow and for the measured discharge to be the same as or close to the survey flow. In practice, the measured discharge will rarely equal the survey discharge for many reasons associated with accuracy of flow measurements, including:

- the measured velocity may not accurately represent the mean velocity in the vertical,
- there may be insufficient measurements across the section to represent the cross-section area and mean cross section velocity accurately, and
- the cross section may not be at right angles to the flow at all points.

The formulation in SEFA means that the measured velocities are reproduced exactly when modeling the survey flow. The method used in SEFA allows for "non-perfect" survey data, assuming that the imperfections will also occur at other flows. For example if the cross-section is not at right angles to the flow, the calculated flow might be 10% higher. In IFG4PHABSIM, the velocities modeled for the survey flow would be about 10% higher than those measured whereas with SEFA they would be exactly as measured. If a higher flow is modeled, SEFA would assume that predicted velocities and depths should sum to a flow that is 10% higher than the modeled flow, i.e. that the angle of the cross-section to the flow remains constant.

Assumption and extrapolation

The assumption is that the pattern of velocity distribution does not change with flow. This is the reason that a survey should be carried out at flows near the flows of interest (usually minimum flow) and that you should be cautious when extrapolating too far. If a survey is carried out at low flow, the velocity distribution is influenced by local roughness elements. As the flow increases the influence of these elements becomes less and the velocity distribution smoother. The sensitivity of AWS analysis to changes in the velocity distribution with flow can be tested by switching VDFs OFF - one of the options. With the VDFs OFF, the velocity distribution is as would be predicted according to the assumption of constant roughness across the cross-section and you can see whether this gives significantly different values of AWS.

Interpretation of VAFs

Velocities at points across a cross-section are calculated as if section and point roughness (VDF or N) does not change with flow. However, roughness (Manning's N) usually varies with flow so it is necessary to adjust velocities to allow for the variation in Manning N.

The velocity adjustment accounts for changes in section roughness and changes in the distribution of point roughness values (point VDF or N values). In the case of the IFG emulation, it also accounts for the difference between the flow calculated from the depth and velocity measurements and the survey flow (best estimate of the flow at the time that the depth and velocity measurements were carried out).

A change in section roughness is the result of applying the rating curve to get the modeled water surface level. The calculated WSL usually differs from that which would be calculated assuming roughness is constant. For example, the exponent of the hydraulic (Manning's equation) rating describes how Manning N varies with flow. If it is negative, Manning's N increases with flow. If it is zero, then Manning's N does not vary with flow. Rating curves fitted to calibration flow gauging will also show some variation in N with discharge.

The other reason for the velocity adjustment is that the distribution of VDFs or N values changes with flow. For example, calculated VDFs are usually high towards the center of the channel and low at the edges (The reverse for N values). If a lower flow is modeled, the low values at the edges will be out of the water and the entire low flow channel will have high VDFs (or low N values). This will over predict velocities (and flow) in the channel, so that an adjustment needs to be made. If VDFs or N values do not vary across the channel, the adjustment will be minimal.

Beta values, as described in the following section, will also affect the velocity adjustment factor and the way in which it varies with flow.

The relationships between Manning's N and discharge can be seen using the menu item Hydraulic calibration>>Ratings>>Display section ratings. The effect of constant VDF or N values can be seen by displaying the VAF/flow relationship (Hydraulic calibration>>Velocity adjustment factors) and pressing Shift-F2.

14.3 Beta for velocity distribution

The constant beta (as described in section 14.1) is introduced to represent the way in which roughness (Manning's N and VDF) changes with discharge. It should not be confused with and can be different from the beta value that is used to describe how Manning's N changes with flow in the hydraulic rating method (MANSQ).

Usually, the roughness will increase as the depth or hydraulic radius decreases. A value of 0 assumes that roughness does not change. A value of -0.3, for example, assumes that roughness increases as depth decreases. Experience shows that the roughness near stream edges is usually greater than in the deeper parts of a stream. A value of -0.3 to -0.5 is recommended for beta, although the default value is 0. A negative value for beta helps solve the velocity distribution problem, where predicted velocities near the edge are often too high.

The term beta is also used to describe the variation of Manning's N with discharge in the Hydraulic rating (MANSQ) and in WSP analysis.

14.4 Zero velocities, water edges and points above water level

The SEFA default method is to treat a zero velocity in the water as a zero velocity so that it takes a VDF of zero, so that there is agreement between measured and predicted point velocity at that point. The automatic calibration of velocity distribution factors assumes that points at and above the stream bank will have the same velocity distribution factor or Manning N as the nearest point in the water.

PHABSIM has treated a zero velocity in water as a missing value, possibly because the N value for a point with zero velocity is infinity, and “borrows” the Manning N of the first point in flowing water towards the thalweg. The PHABSIM emulation replicates this method and “borrows” the Manning N of the first point in flowing water towards the thalweg for all zero velocity points including the water edges and points above water level. With the PHABSIM emulation, a very low velocity can be entered instead of zero, and this will result in velocity predictions of very near zero at that point.

The automatic calibrations can be edited, as described below, and part of the checking procedure should be to examine the VDFs or N values.

14.5 Editing VDFs

Velocity distribution factors (VDFs and Manning N) can be altered if required by simply clicking on a point and dragging it to a new value.

This is an important step if predictions of habitat are to be made at flows greater than the survey flow, because values for points at and above the water’s edge must be estimated.

VDFs usually vary about the value of 1. If the velocity were distributed across the section according to the conveyance of each measurement point then the VDF for each point would be 1. This occurs in situations with uniform flow and cross-section, such as canals. However, in most rivers variations in friction across the section, upstream obstructions such as boulders, and flow patterns caused by bends and eddies cause the VDF to be less than 1 at banks or downstream of obstructions and greater than 1 where flow concentrations occur. Predictions of water velocity at other flows follow the velocity distribution that was measured during the survey and assume that it will not change significantly.

The sensitivity of velocity and habitat predictions can be tested by comparing the flow distributions and habitat/flow relations predicted with the default assumption (the calculated or edited values), the uniform velocity distribution (VDF of 1), and a best guess. The best guess uses the calculated value at the survey flow and then gradually increases the VDF values to 1 as the water level and flow increases.

14.6 Sensitivity to velocity distribution factors

Velocity distribution factors are calculated from velocities measured across each cross-section and the survey flow.

When the survey flow is simulated, the velocity distribution factors are applied to the uniform velocity distribution so that the measured velocity distribution is reproduced.

The uniform velocity distribution assumes that the velocity at each point across a cross-section is proportional to its conveyance or the conveyance of the compartment it represents.

At low flows, the velocity distribution is usually more variable than that in a uniform channel. When higher flows are simulated, it is assumed that transverse pattern of velocities is maintained. This is a reasonable assumption when flows are close to the measured flow. However, when the flow and water level is considerably higher than that surveyed, the features that created the low flow velocity distribution are drowned and the velocity distribution will usually tend towards the uniform velocity distribution. This change from measured velocity distribution at the survey flow towards a uniform velocity distribution at higher flows is modeled in the VDF sensitivity analysis. This analysis is not available if using IFG4 emulation.

The VDF sensitivity analysis plots the habitat/flow relationships with 3 assumptions:

1. VDFs applied (the default as calibrated)

2. VDFs not applied (uniform velocity distribution)

3. Best estimate (changing from calibrated to uniform as flows increase)

The assumption used in calculating best estimates is that the uniform velocity distribution (VDFs of 1) will occur when the water level rises by some amount (the uniform VDF criterion).

This is assumed to occur when the water level rises higher than the larger of:

1. twice the average depth at the survey flow

2. 5 times the average armour size.

i.e., Uniform VDF criterion = Max(2 * mean depth,5 * armour size)

Values of VDFs between the calibration water level and the uniform VDF level are proportionally changed towards 1.

Adjusted VDF = VDF + (1-VDF)*(WL-calibration level)/Uniform VDF criterion

If WL -Calibration level > Uniform VDF criterion then the VDF = 1

Edge values of VDFs are calculated as a proportional increase between the bed level and uniform velocity depth.

Adjusted VDF = VDF + (1-VDF)*(WL-bed level)/Uniform VDF criterion

The predicted velocity distribution using and not using VDFs can be seen by checking the Use VDFs check box in the opening dialogue.

Alternatively, the display of the predicted velocity distribution of any section can be toggled between VDFs applied, VDFs not applied and a best estimate of VDFs as described above.

Toggling is achieved by pressing Shift F1 to get the best VDFs and Shift F2 to get VDfs applied and not applied. The graph title changes to display the VDF option that is shown.

15 Reach and Point Representation

Depths, velocities, attributes, and habitat suitability are calculated for points and integrated over a reach. The calculation of point values can be made in two different ways and these will give slightly different results. The default method which carries out linear interpolation between measurement points should be the best for most purposes. However, the alternate cell method of calculation can be used.

15.1 Calculation of point values

The default calculation of hydraulic and habitat variables uses linear interpolation between point values. For example, values of depth, velocity, attributes and habitat suitability are calculated at 10 interpolated points between measured points.

The alternative calculation of hydraulic and habitat variables assumes that the measured point values represent a larger area - a cell or compartment. The values of compartment depth, velocity, attributes and habitat suitability are calculated assuming that the point value is spread between the midpoints of adjacent points. This is the method used in PHABSIM and RHABSIM.

15.2 Point value

Each point (either measured or interpolated) in a cross-section represents a compartment with an area determined by the distance to adjacent measured or interpolated points and the cross-section length. The compartment width is half the distance between the adjacent points and the compartment length is the percentage of the reach it represents.

15.3 Extrapolation

If modeled water levels are higher than the highest point in a cross-section, the water's edge is determined by linear extrapolation of the two surveyed points at the beginning or end of the cross-section. If the slope is less than 0.05 (1 in 20) then a vertical wall is assumed at 0.01 m from the surveyed start or end of the cross-section. The Check menu in Data will list the edge points and cross-sections where vertical walls will be created. These should be checked to see that this assumption is appropriate.

15.4 Hydraulic habitat suitability

If the compartment is represented by the point values, the characteristics of the compartment are those of the point, the compartment width (1/2 distance between adjacent points) and the compartment length.

Combined suitability index = $fn(Y_i, V_i\ S_i)$

Area weighted suitability = $fn(Y_i, V_i) * (X_{i+1}-X_{i-1})/2$ * Compartment length

Area weighted suitability used to be called weighted usable area. The terminology has been changed to make the meaning of index clearer.

Multiplication of suitability indices is the default method for the calculation of the combined suitability index. Other methods of combining suitability indices (geometric mean, minimum) can be selected in using the File>>Preferences>>Calculation menu.

15.5 Interpolation between point measurements

The representation of a reach as compartments with values of depth, velocity, and attributes is suitable for single variables that vary linearly between measurements. However, habitat suitability depends on depth, velocity, and substrate and is not a linear function. This means that the representation of a compartment by measured point values or by the average of adjacent points may not be adequate for the calculation of habitat suitability. This will depend on the spacing of the survey measurement points and the habitat suitability curves.

For example, consider the calculation of habitat suitability where the preferred habitat is a depth of between 0.2 and 0.3 m. Two adjacent points are measured at depths of 0.1 m and 0.5 m with a linear increase in depth between them. The average depth and velocity are probably represented adequately by the average of the measurements. However, habitat suitability at both points is zero (depth not in the 0.2-0.3 range), so that the compartment value of habitat suitability is zero. This is obviously inaccurate because the habitat is suitable at some point between the two measured points. Compartment values, either as points or averages, are an approximation and the degree of potential error will depend on the survey spacing and the habitat suitability curves.

The alternative is to interpolate values of depth, velocity, and attributes (e.g., substrate) between measured points and to integrate habitat suitability over the compartment.

This is the default method of calculation of habitat suitability (June 2000) and may produce slightly different results to those calculated prior to June 2000, when the default method was to use point value compartment representation.

An example of the effect of interpolation of habitat can be seen by changing the interpolation grid while displaying a plan view of the reach (Plan in the Model menu ). The different interpolation schemes are also represented graphically in the Model menu under Measured section habitat  and Point habitat  displays, where interpolated values are displayed as "continuous" data and point values without interpolation are displayed as histograms.

If the interpolation option is checked, as it is by default, values of depth, velocity, attributes and thus habitat suitability etc. are interpolated at equally spaced intervals (10) between points. This gives a better measure of habitat suitability, assuming linear interpolation is appropriate.

In some cases, interpolation of attributes between measurement points might not be appropriate and this depends on how the suitability curve for the attribute is formulated. If the suitability curve is a continuous function such as for depth, velocity and percentage of a substrate category, linear interpolation would be appropriate. If the suitability curve is not continuous, such as when an attribute that takes multiple values (usually 0 or 1) for the characteristic of the measurement point (e.g., cover, overhanging bank, shade etc.), it would not be appropriate to interpolate between these characteristics but they can still be used in habitat evaluation. One way would be to not use any interpolation between measurement pints. However, a better method may be to calculate habitat suitability from interpolated depths and velocities with the attributes at the point by setting the check boxes in the File>>Preferences>>calculation menu.

The difference between habitat and velocities etc. with and without interpolation can be seen by plotting section habitat (Model menu under Measured section habitat) with the interpolation switch on then off.

15.6 Calculation of average depth and velocity

Average depths and velocities can be calculated in different ways depending on the averaging or weighting scheme used and whether the average is across a cross-section or for the reach. Reach averages are the sum of cross-section averages weighted by the distance or proportion of habitat represented by the cross-section.

Across a cross-section, the average depth is equal to the cross-section area divided by the water surface width. For a reach, the average depth is the sum of the average depths at each cross-section weighted by the cross-section weight. The reach average depth calculated in this way is not equal to the reach average cross-section area divided by the reach average width.

The average velocity across a cross-section is calculated as the width-averaged velocity, where every velocity is weighted by the width it represents and average velocity is the sum of the weighted velocities divided by the water surface width. The width-averaged velocity is not equal to the average cross-section velocity that is usually used in hydraulic computations. The average cross-section velocity is the sum of the velocities weighted by the area they represent divided by the cross-section area. This is equal to the flow divided by the cross-section area.

16 Calculation of water velocities

Predicted water velocities, calculated as described in Section 14.1, are displayed for a specified flow range and increment, along with the measured water velocities.

This can be used to check that the calibration procedures have been carried out correctly.

The first time that a range of flows is modeled, the default flow range is used. The default flow range is calculated to give a range of flows based on a reasonable extrapolation of rating curve from 0.5 times the minimum of the survey and calibration flows (Qmin) to 2 times the maximum of the survey and calibration flows (Qmax). Qmax and Qmin are then rounded for plotting with a default interval of (Qmax-Qmin) divided by 10.

Simulations of flows higher than the survey flow should plot at higher velocities than those measured during calibration, simulation of the survey flow should reproduce the measured velocities, and velocities at flows lower than the survey flow should be lower than calculated flows.

In some situations, an increase in water velocity may be predicted at low flows. This occurs when the flow is constrained in a narrow channel, such as between boulders, and is feasible.

If the option to use VDFs is not checked, velocities are predicted according to the conveyance of each compartment, and the effect of roughness, obstructions, and flow concentrations on the velocity distribution can be determined.

The effect of changed the VDF assumptions can be seen on the velocity distribution.

The predicted velocity distribution using and not using VDFs can be seen by checking the Use VDFs check box in the opening dialogue.

Alternatively, the display of the predicted velocity distribution of any section can be toggled between VDFs applied, VDFs not applied and a best estimate of VDFs as described above.

Toggling is achieved by pressing Shift F1 to get the best VDFs and Shift F2 to get VDfs applied and not applied. The graph title changes to display the VDF option that is shown.

The predicted water velocities in SEFA will differ slightly from those predicted by IFG4. When SEFA is used to predict the water depths and velocities at the survey flow, it will predict the depths and velocities that were measured in the field. In contrast, IFG4 (PHABSIM) will only reproduce measured depths and velocities when the measured data are “perfect”, that is the rating curve goes through the stage measured at the survey flow and the flow calculated from the sum of the measured depths and velocities is exactly the same as the best estimate of the reach flow. SEFA has a calculation option in Preferences>>Calculation options>>Hydraulic that allows IFG4 emulation to be selected and used to demonstrate the effect of this change in calculation method.

This method of flow calculation used in SEFA is considered more flexible and more accurate in some circumstances (Section 14.1), and differs slightly from the methods used in RHABSIM, PHABSIM and RHYHABSIM. For this reason, predicted velocities will be slightly different to those predicted in the other programs.

16.1 Special Applications

It is possible to use SEFA to predict velocities based on cross-section geometry without measurements of water velocity at each cross-section. For example to reduce field effort, a survey of a stream could measure cross-section profiles and water levels at many cross-sections, and measure the cross-section and velocities at only one cross-section.

These data would be entered in the normal way. For the cross-sections without any velocity measurement, no velocity or revolution/time data would be entered so that the data would be:

offset depth attributes.

The cross-section with velocities would be entered normally, specifying meter constants, revs and times, or just entering velocities:

offset depth velocity attributes

or

offset depth revs time attributes.

When importing a file with depth data only, SEFA assigns a velocity distribution factor of 1 to each data point and calculates a theoretical velocity. When flows are calculated, the depth data flows do not necessarily match those calculated for the cross-section with velocity data or with the known flow. However, when the survey flow (estimate of flow at the time of the survey) is set in the calibration procedure, the velocities are adjusted so that they calculate that flow. Once calibrated, the cross-sections with only depth data appear the same as cross-sections with velocity, except that their velocity distributions are based on VDFs of 1 (i.e., velocity proportional to the hydraulic radius to the power of 2/3 or 1/2).

If water velocities of zero included with depth data, SEFA assumes they are correct and will always predict zero velocity at all points across that cross-section.

17 Viewing data

17.1 Reach and cross-section summary

For each reach, a text summary can be displayed by selecting the Survey Summary in the Hydraulic Habitat menu.

This lists:

- cross section spacing and weighting factors
- total number of cross-sections and measurements
- average spacing of measurements across each cross-section
- average spacing of sections through a reach
- total number of measurement points in water
- average spacing of sections through a reach

Text and tables can be copied to the clipboard by either clicking the copy icon  or selecting copy in the edit menu or by using the keyboard shortcut Ctrl C.

When text is pasted into a document tables can be reformatted using the Table AutoFormat function.

17.2 Longitudinal river profile

For water surface profile modeling in a representative reach, cross-sections must describe reach geometry in both longitudinal and cross-sectional profile. This means that a representative reach approach must be used, where the elevation of every cross-section is related to the same datum and sections are close enough to represent adequately both the variation in cross-section area and longitudinal profile.

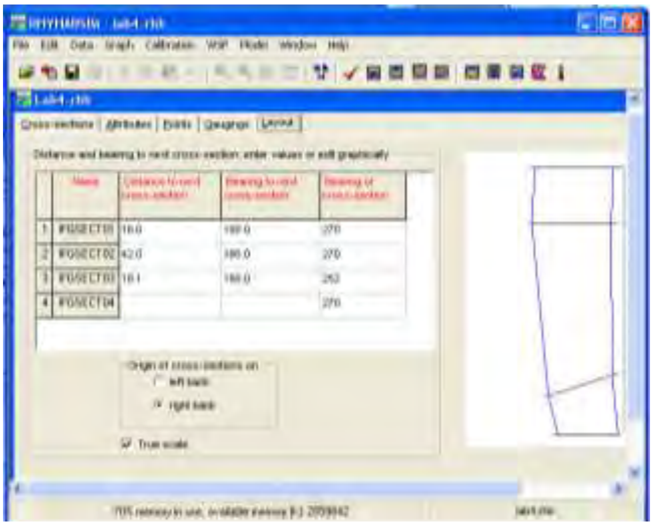
If cross-sections are selected with stratified random approach (habitat mapping), the data cannot be used for water surface profile modeling because the longitudinal profile is not defined.

The longitudinal water surface profile can be viewed under the WSP menu by selecting the Calculate WSP item. This displays the water surface level and mean bed level at each cross-section along the stream length, beginning at the first cross-section, usually the most downstream and lowest water level.

The plot is only a true profile if cross-section water levels are referenced to the same datum.

17.3 Reach layout

The layout of a reach is specified on the layout page of Edit/Display>>Edit/View menu.



The geometry of the reach is described by the layout. The layout specifies the bearing and distance to the next cross-section and the bearing of the cross-section itself. These values are automatically calculated from zero and end coordinates of cross-sections, if coordinates are entered on the Cross-section tab.

The origin of a cross-section is the point where the offset is zero. The locations of cross-section origins are given as bearings and distances from the first to second cross-section, second to third, etc.

The reach is plotted according to the bearings, with the page oriented North-South. If the bearings of all cross-section are 0 degrees, the reach will lie North-South with the first cross-section at the bottom of the page. If all bearings are 180 deg, the first reach will be plotted at the top of the page with all other cross-sections below it.

The bearing of each cross-section to the reach is also specified with respect to North-South.

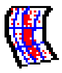
If the cross-section is at right angles to a reach with bearings of 0 (i.e., going north) and the zero offset is on the right of the page the cross-section bearings will be 270 deg. If the zero offset is on the left of the page, the cross-section bearings will be 90 deg, if at right angles to the reach.

There is no way of specifying a change in angle part way across the cross-section.

The layout of the reach can be edited graphically by clicking on the cross-section to be edited when in the Layout page of Edit/View in the Edit/Display menu. Edit "handles" are then displayed. Click and drag the square handle to move, but not rotate, the section. This alters the origin and distance between sections. Click on the circle to rotate the cross-section. As the sections are moved the values of distance, bearing or offset, and angle are displayed in the table. Values can also be entered into the table directly.

If true scale is checked, the reach is plotted to a true scale (X and Y scales equal). If not checked the scale optimizes the area shown, but distances and angles will be distorted.

17.4 Plan View



A plan view of the reach can be displayed using Edit/Display>>Display>>Plan. The default plan is for the survey flow.

Cross-sections are plotted with X as the offsets (distance across the section) and Y as the distance upstream. The baseline is shown as a dotted line. The base line is the line of zero cross-section offsets. If you click on the plan, XY coordinates and other parameters are displayed.

If the reach is a representative reach, contours of velocity, depth, shear velocity, substrate size and attributes can be displayed by clicking on the table that displays the minimum, mean, and maximum values of these reach characteristics.

If the reach is multi-channel or habitat mapped, the display is rectangular with the length of each cross-section represented by its weight.

Use graph options to:

- set linear or smooth interpolation between sections
- change contour intervals,
- change grid intervals (resolution).
- display legend

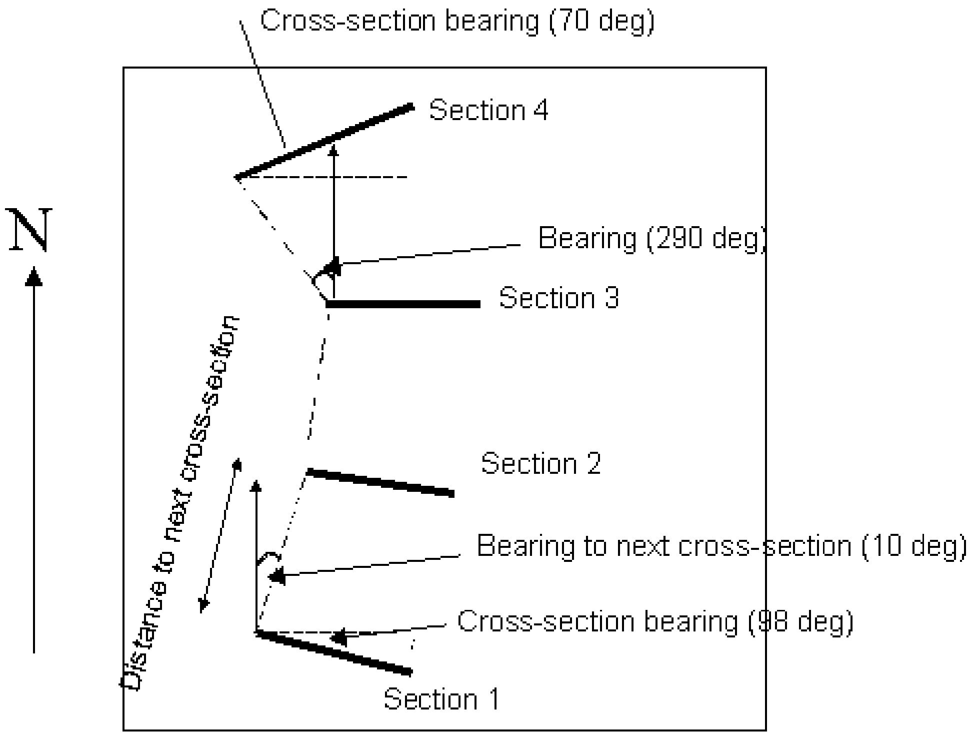
Contours for other flows can be displayed simply by changing the flow listed on the display. A range of flows can be displayed successively by setting a minimum, maximum and interval and pressing the Flows button.

The color range and grid scale for each flow can be fixed in Graph Options so that the same color gradient and range is used for all flows.

The geometry of the reach is described by the layout described in the previous section.

The plan can be copied to the clipboard, saved as a file, or listed as a text file specifying the depth, velocity etc. at each grid node.

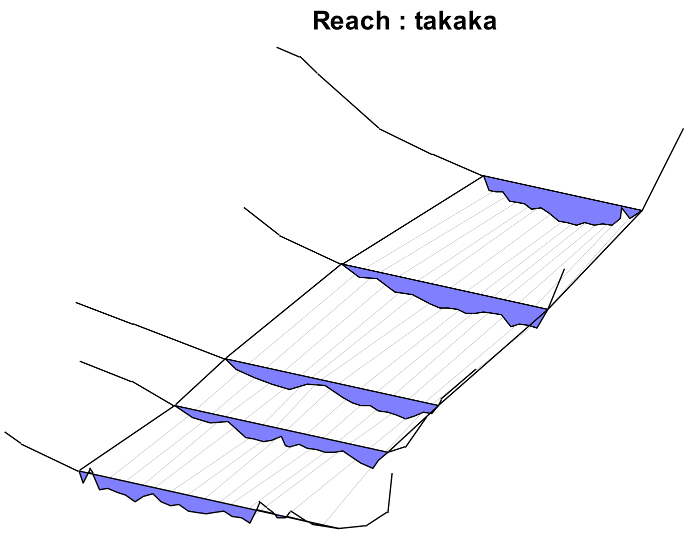
If true scale is checked, the reach is plotted to a true scale (X and Y scales equal). If not checked the scale optimizes the area shown, but distances and angles will be distorted.



17.5 Isometric view of reach cross-sections

An isometric view can be rotated between 0 and 90 degrees. Cross-sections are joined by a series of lines equally spaced across the section and are shown as verticals on the cross-section.

The presentation style of this display can be altered in the Edit/Display>>Graph options menu.



18 Hydraulic calculations

18.1 Hydraulic properties

The Section Hydraulic Properties menu option of Hydraulic Habitat>>Geometry calculates the variation of cross-section area, hydraulic radius, wetted perimeter and stream width with elevation is displayed for each cross-section.

If the data is a "representative" reach, i.e., the distance between cross-sections and their elevations relative to the same datum, the Reach area/volume menu option of Hydraulic Habitat>>Geometry calculates the reservoir area/volume curves. It shows the water volume of the reach, assuming a horizontal surface. The Surface area is displayed using the select button on the bottom of the window.

The surface area and volume between each pair of cross-sections is calculated assuming that they vary linearly between cross-sections.

Volume between 1 and 2 = (Area 1+Area 2)/2 * Distance between 1 & 2

18.2 Substrate size

Substrate size is used to calculate variables such as shear stress and sediment movement in a number of sediment and display analyses. For example, the median armour size (d50) mm is used to calculate flushing flow effectiveness at each point.

The substrate size at each measurement point is calculated from substrates specified at that point by multiplying the proportion of each substrate index by its size.

There are 8 substrate indices, for substrate “types” bedrock, boulder, cobble, gravel, fine gravel, sand, silt, and vegetation. However, any attribute can be identified as a substrate (using the Edit button in the Attributes tab in Edit/Display>>Edit/View menu) and a size in mm assigned in the Sediment>>Set substrate sizes menu.

The median substrate size is determined from the percentage composition and the average size of the substrate category where 50% of the substrate is smaller than that type.

For instream habitat analyses the percentage of a substrate type is the percentage of the bed area covered by that substrate size category. This method is used because substrate suitability (i.e., based on substrate size category) is one of the factors that are multiplied by area to determine area weighted suitability (AWS).

The substrate “type” names and default sizes (mm) for substrate indices 1-8 are vegetation (25), silt (0.01), sand (1), fine gravel (5), gravel (36), cobble (160), boulder (256), bedrock (1000), respectively.

18.3 Hydraulic rating curves

Rating curves based on cross-section geometry and gaugings can be calculated by Manning’s equation

*V = 1/n * R^2/3 * S^1/2*

Where n = Manning’s n, S = slope, R = Hydraulic radius – hydraulic radius at SZF

S is assumed constant.

When the hydraulic method is used in pools (Fr < 0.18 at calibration flow) the hydraulic radius (R) and cross-section area are reduced by the hydraulic radius and area at the SZF. When the Fr is greater than 0.18 no adjustment is made for the SZF.

With only one measurement of flow, the roughness coefficient, Manning N, is assumed constant with flow. With 2 or more gaugings, values of n are calculated for each flow and a log-log relationship between and the roughness constant and either flow or hydraulic radius derived by least squares.

*N = constant * Q^beta* with roughness varying with flow

*N = constant * (Hydraulic radius* – hydraulic radius at SZF*)^beta* with roughness varying with hydraulic radius

The former is the default assumption.

18.4 Cross-section conveyance, hydraulic radius and integration

Conveyance is a measure of the capacity of a channel or channel subsection the convey water. The traditional measure of conveyance includes friction (Manning's N) but if friction is constant then conveyance is a measure of the geometry of the channel. Conveyance is used in the calculation of velocities across a channel, in the calculation of hydraulic rating curves, and is used in water surface profile modeling.

*Conveyance = A * R^2/3*

The conveyance of a section is integrated over the whole cross-section as the sum of the compartment areas times their hydraulic radii to the power two-thirds.

The hydraulic radius for a cross-section is calculated from the integrated conveyance as (cross-section conveyance/cross-section area)^(3/2).

Integration is the preferred method because when conveyance is calculated in this way, its variation with level forms a smooth curve and gives better results in water surface profile modeling.

18.5 Water surface profile modeling

The water surface profile (WSP) model allows water surface levels to be modeled using the principles of conservation of energy and momentum between cross-sections. This approach is only possible with 'Representative reach' data and is most useful in low-gradient streams. The profile is calculated from the downstream cross-section and the predicted water levels (when two or more profiles are modeled) are used to form another (fourth) rating curve for all cross-sections. This is particularly useful for rivers where the upstream cross-sections could not be surveyed more than once or where the ratings curve types (1), (2) and (3) for other reasons are unreliable. However, the tendency is to use habitat mapping because it is less time-consuming in the field and the cross-sections can be spread over a larger area.

The velocity head coefficient (VHC) converts the mean velocity head ($Vm^2/2g$) to the true velocity head loss. If the velocity does not vary, across the section then these two will be the same but normally the true velocity head will 1.5 to 3 times greater. It is calculated from measured velocity by integrating the velocity head across the section:

VHC = Sum(V_i^3 x Ai)/(V_m^3 x A)

However, the integration method of calculating conveyance is used and the velocity head coefficient is calculated from the section geometry, rather than from measured velocities.

The velocity head coefficient (VHC) is:

VHC = (Compartment conveyance^3/Compartment area^2) x (Area^2)/Conveyance^3

Integration methods for conveyance and velocity head are not used where the cross-section contains underwater overhangs. In fact, although cross-section data with overhangs can be processed habitat and velocity predictions will be incorrect if the overhang is underwater.

Conveyance can be calculated as an arithmetic or harmonic mean of two cross-sections.

19 Hydraulic Habitat analyses

There are three steps to simulating hydraulic conditions and then evaluating habitat suitability for those conditions.

First, the rating used to predict water levels for the required flow range can be selected. The default is a log-log stage-discharge relationship.

Second, habitat suitability curves used to evaluate the amount of habitat at different flows can be selected. The simulation can proceed without any curves being selected.

Third, the flows to be simulated are specified, depth, velocity, and point habitat suitability calculated for each point in the reach, and then results are summarized.

The first time that a range of flows is modeled, the default flow range is used. The default flow range is calculated to give a range of flows based on a reasonable extrapolation of rating curve from 0.5 times the minimum of the survey and calibration flows (Qmin) to 2 times the maximum of the survey and calibration flows (Qmax). Qmax and Qmin are then rounded for plotting with a default interval of (Qmax-Qmin) divided by 10.

After the suitability curves have been selected, the modeled habitat at the survey flow is obtained by clicking 'Model', 'Measured section habitat' (plots) and 'Measured reach habitat' (numbers). The next item, 'Measured passage', calculates the flow (and width) required for fish passage; any minimum depth and maximum velocity can be specified.

The modeled habitat for points ('Point habitat'), cross-sections ('Section habitat') and the reach as a whole ('Reach habitat') can be viewed for any range of flow (which can have unequal flow increments, click the box in the dialogue). For these plots, it is possible to select a subset of sections (click on 'Section' under 'Select' to the right in the dialogue; click on 'Clear' to go back to the default option where all sections are selected). For the 'Section habitat' and 'Reach habitat' it is possible to pull in cross-section data from another file. Click on the 'Reach' button under 'Select' to the right and select a file. You are then asked whether you want to combine the selected file with the previous file. If you answer 'yes' to this question, the files will be merged (but can be un-merged by clicking on 'Clear' and you are back with the original file), and the 'Sections habitat' will show all sections from both files and the 'Reach habitat' will show the total habitat for all selected reaches on the same plot. The merging is indicated by a plus between the two names in the titles of the plots. If you answer 'no' to the question about merging, one plot is produced for each reach (use the arrows to move between them). The range of flow can be selected for each section by clicking 'Vary flow between sections' (but the number of flows modeled must be the same for all reaches).

In all habitat plots ('Point', 'Section' and 'Reach') you can use the 'Select' button below the plot to view other parameters such as depth, width, Froude number, etc. The 'Reach habitat' curve is the main outcome of the model, showing the physical habitat area (also called area weighted suitability, AWS) or reach average suitability index (CSI) varies as a function of flow. AWS is expressed as absolute values in terms of Hydraulic habitat in m^2 per m river (or m of river width). Use the 'Select' button to change between AWS and CSI. The AWS-flow curve typically increases with flow until a peak followed by a slow decrease.

When a reach has been modeled, the AWS/Flow results can be saved, not as a separate file, but as part of the SEFA file. The suffix of save AWS/Flow results is the date and time, so that it is possible to save a series of results. The calculations options used to produce the results are also saved and can be viewed if the results are subsequently used as an overlay or when applying and AWS/Flow relationship to a hydrological time series.

If AWS/Flow relationships have been saved, either in the SEFA file that is open or another SEFA file, those relationships can be overlaid on the AWS/Flow graph that is displayed. Select AWS/Flow Relationships>>Overlay AWS/Flow relationship or right click on the graph and select Overlay AWS/Flow relationship. All saved relationships are displayed along with their calculation details. Select one and click OK.

For reach data, the 'Plan' view provides a colored map of various parameters (hydraulic or habitat). The selected parameter is highlighted in the list of attributes to the left for the flow indicated in the top box (change the flow and press enter for an update of the plan view). For representative reaches contours of the parameters can also be displayed. Click on the left-hand mouse button to see values of hydraulic parameters and habitat in the reach. Options (open the dialogue box under 'Edit/Display>>Graph options') are provided for this view.

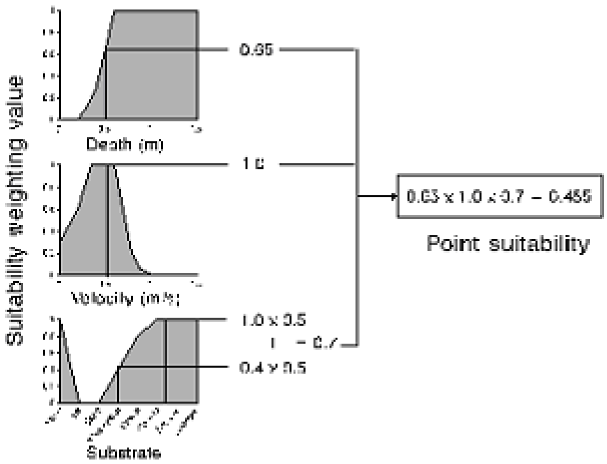
19.1 Point suitability

Habitat suitability is calculated from the water depth, velocity, and substrate between points and any other user variables that are specified in the suitability curves.

Habitat can be calculated for any combination of depth, velocity and substrate by un-selecting the appropriate variables. User-specified variables can also be used to calculate habitat and the number of independent suitability functions is unlimited and not just restricted to depth, velocity and substrate.

The suitability of the value of each variable is determined from the selected habitat suitability curves. The suitability varies between 0 (unsuitable) and 1 (ideal). The overall suitability of a point (CSI) is the product of the suitability of depth, velocity, and substrate (if applied). This means that if any suitability is zero then the point is unsuitable for that habitat use. If using the SEFA substrate categories as in the example below, substrate habitat suitability is calculated from the percentage of each of those substrate categories. The substrate suitability at measurement point is the sum of the suitability for each category multiplied by the percentage of that substrate category at the point.

Options can be selected to form the combined suitability index (CSI) as the average or geometric mean of the suitability values.



Each measurement point represents a portion of the stream width and area. This is half the distance between the points on either side. SEFA interpolates linearly at 20 points between measurement points. The area of each interpolated point (compartment area) is the width multiplied by the percentage of reach that the cross-section represents.

Average velocity and attributes are calculated as area weighted averages i.e.,

Sum(Value x dA)/Sum(dA),

where dA = dWidth x Reach length

This results in average velocities that are slightly different to the cross-section average of:

V = Q/A

or weighted section averages calculated as

V = ((Sum(V x dWidth)/Width) x Section length) / Reach length

The reach length is either half the distance between the adjacent cross-sections (i.e., a representative reach) or the percentage of reach that the cross-section represents (i.e., the cross-section weight based on habitat mapping).

The cross-section weight can be specified in an ASCII file or entered, and if no value is entered or specified, it is calculated from the cross-section distances.

19.2 Summation of habitat suitability

Habitat suitability can be presented as values between points in a cross-section or summed for a cross-section, or for the whole reach. Cross-sections with multiple channels or braids are treated similarly, with the total area in the cross-section summed over each braid. The total amount of habitat in the reach is summed for each flow and each point by multiplying the habitat suitability of a point by the area it represents and then by absolute value of the percentage of the reach represented by the cross-section.

In all cases, the weighted usable area is weighted by the cross-section weight, as listed in Edit/Display menu. The value listed is the value specified in the ASCII file that was imported or the value entered, and if no value was entered or specified it is calculated from the cross-section distances. This means that it is possible to have cross-section weights that differ from those that would be calculated from the cross-section distances.

The measured water depths, velocities, and substrate are used to evaluate the habitat suitability between all measurement points, the area weighted suitability of each cross-section and over the whole reach.

19.3 Area weighted suitability and average combined suitability index

Habitat is expressed either as area weighted suitability (AWS) in units of m^2/m or ft^2/ft or as the average CSI for the reach or cross-section. AWS used to be called weighted usable area, which was misleading because the index is not an area.

Area weighted suitability (AWS) is the combined habitat suitability index (CSI) weighted by area. The CSI based on the physical character (water depth, velocity and substrate and other attributes, if required) specified in the habitat suitability curves. If habitat suitability is specified so that suitable habitat has a weight of 1 and unsuitable habitat a weight of 0, the area is the usable area in m of width or m^2 per metre of reach (m^2/m or ft^2/ft). If habitat suitability curves are specified with weights of between 0 and 1, AWS is an index of suitability and not a measure of physical area.

CSI is calculated by multiplying the habitat suitability (between 0 and 1) for each of the criteria, usually depth, velocity, and substrate (if applied), at a measurement point. Optionally, CSI can be calculated as the geometric mean or the arithmetic average of the habitat suitabilities.

The AWS is calculated by multiplying the CSI at each point by the proportion of the reach area represented by that point (i.e., the width and cross-section weight) and summing over the reach.

The reach CSI will have a value of between 0 and 1, with 0 if there is no suitable habitat in the reach and 1 if the whole reach is ideal habitat. The flow that creates conditions with the highest CSI is usually slightly less than the flow that provides the maximum AWS.

Files with no substrate

If a file does not contain substrate categories, the option to apply substrate suitability will not be enabled and no substrate suitability values will be applied when calculating CSI. If multiple files are modeled together and the first file contains no substrate categories, then CSI for all files will be calculated without substrate suitability. However, if the first file contains substrate categories and you check substrate, substrate suitability will be applied to all files. If one of the files contains no substrate categories, CSI will be calculated without substrate suitability.

Depth

The mean depth in a section is calculated as the cross-section area divided by the cross-section width. For a reach, mean depth is averaged over the reach by weighting by the percentage of the total reach represented by the cross-section.

The mean depth in a reach does not necessarily equal the mean reach area divided by the mean reach width.

Velocity

The mean velocity is the mean velocity across the section or reach rather than the mean velocity within the section and the two are not necessarily the same. The mean velocity within a section is calculated by dividing the flow (Q) by the cross-section area (A). The mean velocity across a section is calculated from the velocity weighted by the water surface width over which it occurs. The mean velocity over a section is the area weighted average i.e.,

Sum(V x dA)/Sum(dA)

The mean velocity over a reach is

Sum(Sum(V x dA)/Sum(dA) x Section weight)/Sum(Section weight)

Pool, run, riffle

The proportion of run, riffle and pool habitat is calculated from the predicted Froude number at each measurement point. Points with Froude numbers in excess of 0.41 are considered to be riffle habitat, and points with Froude numbers of less 0.18 than are considered pool habitat. Intermediate values are run habitat.

Attributes

All attributes or substrates are averaged for each flow and are summarized.

19.3.1 Multiple reaches

A number of reaches (reach button) may be analyzed and the results incorporated into an overall summary. In this way, different reaches can represent different habitat types and be averaged to represent a larger section of the river.

Measurements of compartment length, width, velocity, depth, and habitat suitability at each measurement point below water level are listed in the text display.

When multiple reaches are analyzed, each reach is weighted according to the cross-section weights. For example, if the sum of the reach weights for reach1 is 100% and the sum of the reach weights for reach2 is 100%, each reach will be weighted equally by 100%. However, if the sum of the reach weights for reach1 is 40% and the sum of reach weights for reach2 is 80%, reach 2 will be given twice the weight of reach1 because reach1 results will be weighted by 40% and reach2 results weighted by 80%.

There is no requirement for reach weights, for single or multiple reaches to sum to 100%, although normally this would be the case.

19.3.2 Varying flows

If flows are to be varied between cross sections for predictions, there are two options. Either divide the reach up into smaller reaches each with the same flow or analyse as a single reach.

Single reach with varying flows

To vary flows in a single reach requires setting the flow to be modeled for each cross-section by checking the Vary flow between sections checkbox.

When you do this each reach is modeled for the flows you have specified. The critical thing is the number of calculation steps should be the same (SEFA won't allow otherwise). This is because the AWS and other variables are summed over all cross sections for each flow step.

The procedure would be to decide on a flow range and interval for the section with the lowest flow range i.e. section 0 (usually the most upstream section and the first in the data) - let's say the flow range is 0 to 500 at intervals of 50. This would give 10 steps (500-0)/50.

Then for sections where the flow will be higher section n, decide on the flow at the section that would occur when the flow at section 0 is 0 - let's say 55. Then decide on the flow that would occur when section 0 is at its maximum value of 500 - let's say it would be 655. Then specify the interval so the number of steps is the same as in Section 0 i.e. (655-55)/10 or 60.

The first step would calculate AWS for section 0 at 0 flow and then AWS for section n with a flow of 55 and add them together. The second step would add AWS for section 0 at a flow of 10 with AWS at section n for a flow of 115 etc.

Section 0 is the reference flow and the flows in the output refer to the flow at that section. If Section 0 is not the first then the output flows would refer to the first flow in the reach.

Multiple reaches with same flow at each cross-section

To model as multiple reaches, you would set the flow range to be modeled for the reach (with "vary flow between sections" unchecked).

The first reach would usually be the most upstream reach and the flow in this reach acts as the reference flow.

The first reach might model flows of 0 to 500 at intervals of 50.

Next click on the Reach button (top right) and specify the flow range for this reach in the same way as above - i.e. with the same number of steps as in the first reach (55 to 655 at intervals of 60).

19.4 Bioenergetic modelling

Unlike instream habitat models, bioenergetic models are not in common use in evaluating how potential fish abundance varies with flow in a river. Part of the reason is the apparent complexity of drift-feeding bioenergetic models and the other is a lack of integration between the hydraulic modeling in instream habitat analysis and bioenergetic calculations. Drift-feeding models have an advantage over simple habitat analysis in that they can integrate the effects of physical habitat (velocity and depth) and prey abundance (invertebrate drift). The output of a bioenergetic model is the Net Rate of Energy Intake (NREI) which is the difference between the energy gained through feeding and the energy used in obtaining the food. NREI can be integrated over a river reach in the same way as habitat suitability. When the model is applied, points in the river with a positive NREI are considered suitable for fish and those with the highest value are considered most suitable. If fish are selecting energetically efficient locations in a river, then there should be a relationship between NREI and fish density or presence/absence assuming that fish are selecting locations which are energetically advantageous.

A simple programme (BioenergeticsHSC) generates values of NREI over a range of water depths and velocities, given the fish size and position in the water column, water temperature, bed roughness and invertebrate drift rate. A choice of swimming cost models is given. Various combinations of fish size etc. can be generated and saved as a generalized additive model (GAM) in a zipped file. The GAMs using depth, velocity and an interaction term explain 98% or more of the variation in NREI calculated by BioenergeticsHSC.

SEFA (system for environmental flow analysis) reads the zipped file and the GAM acts in the same way as habitat suitability curves in an instream habitat analysis. The procedure in SEFA is to select fish size, bed roughness, water temperature and swimming cost model. NREI is then modeled for a range of flows for the specified drift rate, which can either be constant or vary with water velocity.

There are a number of advantages of this system. It is easy to generate NREI for a range of input values to test the sensitivity of the model to the parameters. The most important parameter that determines optimal flow for drift-feeding fish in a river is the swimming cost model. Using the tool, it is possible to determine whether swimming cost models predict variation in swimming cost with velocity and with fish size that matches well established swimming theory. When using SEFA, it is possible to determine the sensitivity of NREI, or more importantly the shape of the NREI-flow relationship, to invertebrate drift density and whether it varies with flow or not.

19.4.1 Calculation of net rate of energy intake (NREI)

The bioenergetics model (BioenergeticsHSC) has two main parts - the energy derived from drifting invertebrates (prey) and energy used in swimming and capturing prey (swimming costs). The difference between these two parts is the NREI. The value of NREI increases as velocity increases but then decreases when swimming costs become too high (Fig. 19.1).

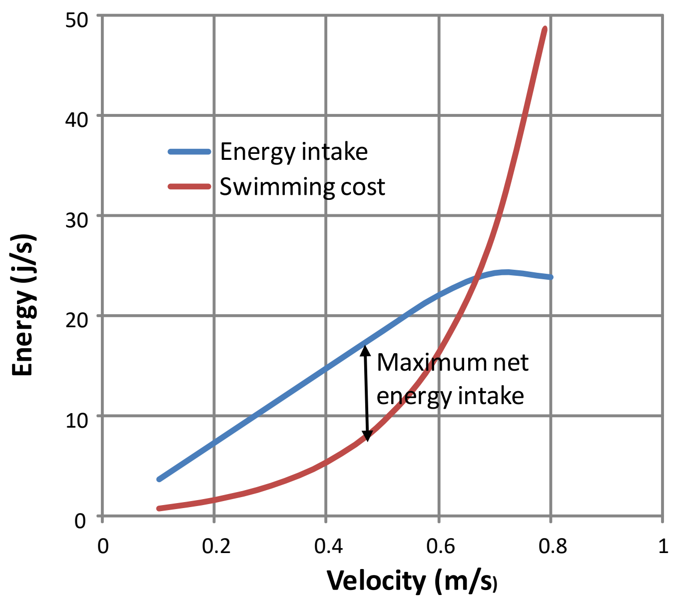


Figure 19.1: Relationship between energy intake from prey capture and fish swimming costs. Positive values of NREI occur when Energy intake exceeds swimming costs.

The input parameters for the model are:

- Prey drift density and size distribution
- Fish length and weight
- Fish distance above the stream bed
- Water temperature
- Bed roughness – effective height of surface substrate
- Swimming cost model
- Assimilation model

The energy value of prey captured is calculated from the number of prey and their weight and energy value. Not all of this energy is assimilated by the fish and the energy intake must be reduced according to the efficiency of assimilation. Assimilation efficiency should decrease as food consumption increases. The Wisconsin method as described in Rosenfeld & Taylor (2009) adjusts assimilation according to energy intake to a degree, although it may over-estimate energy intake by about 5% at maximum consumption rates.

The energy cost of swimming at the fish's focal point and in prey capture is more uncertain than estimating energy intake. The swimming cost has a significant effect on the optimum velocity predicted by the bioenergetics model.

19.4.2 Example application

Hayes et al. (2007) described the application of a bioenergetics model in a reach the Travers River. An instream habitat model of this reach was used to demonstrate the use of the bioenergetics tool and SEFA in predicting the variation with flow of area weighted NREI compared to the variation in habitat (AWS).

The BioenergeticsHSC programme predicts NREI for a range of water depths and velocities. The programme was initially developed in Canada by Sean Naman, Jordan Rosenfeld and Jason Neuswanger and is described in Naman et al. (in prep).

The first step is to run BioenergeticsHSC (Fig. 19.2) to generate a set of generalised additive models (GAMs) that can then be used by SEFA. GAMs are necessary because the relationship between NREI, depth and velocity should contain and interaction term to allow for the way the optimum velocity increases with depth (Fig. 19.3).

The input parameters are:

- Prey drift density and size distribution
- Fish length and weight
- Fish distance above the stream bed
- Water temperature
- Bed roughness – effective height of surface substrate
- Swimming cost model
- Assimilation model.

The GAMs were developed for a 50 cm trout weighing 1300g at a height of 10 cm above the bed with clear water and water temperature of 16°C. The roughness height was assumed to be the d_{65} size[6] of about 100 mm. The Wisconsin assimilation model for rainbow trout was used because it adjusts assimilation efficiency for food consumption rather than assuming a constant assimilation efficiency. A uniform vertical distribution was used for drifting prey. Drift concentrations of 0.4 and 0.8 /m^3 with only one size class (7.5 mm) were used as these were the drift concentrations used by Hayes et al. (2007). GAMs could be developed for any fish length, swimming cost sub-model, roughness etc. and each GAM stored in a zipped file. Hayes brown/rainbow and Hayes rainbow swimming cost sub-models were used.

Hayes rainbow trout sub-model was the only swimming loss model that met the test of predicting the variation in swimming loss with velocity and fish size.

[6] 65% of the substrate particles are smaller than this size.

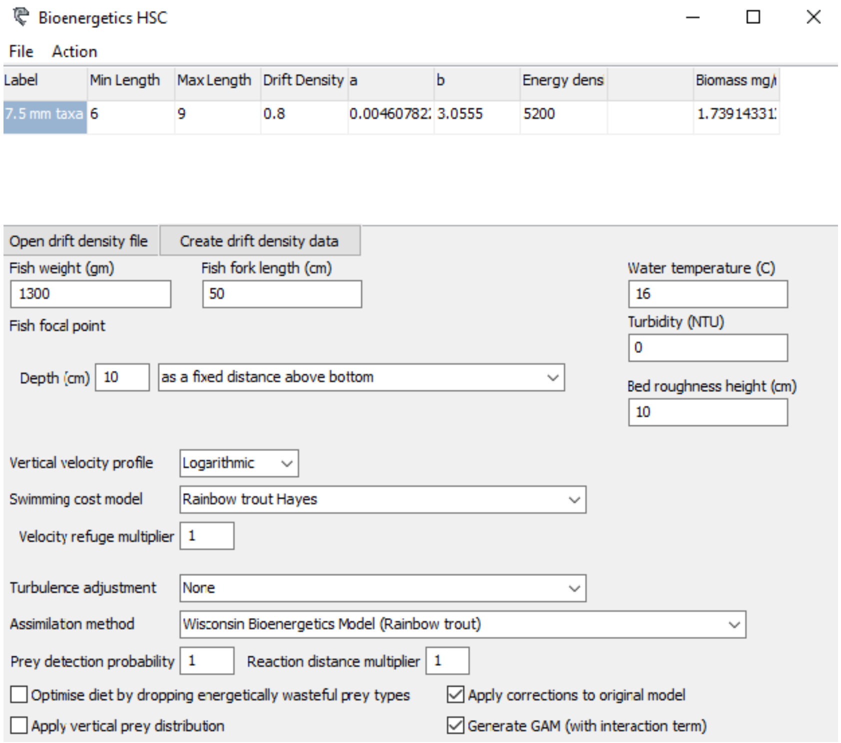


Figure 19.2 BioenergeticHSC dialog

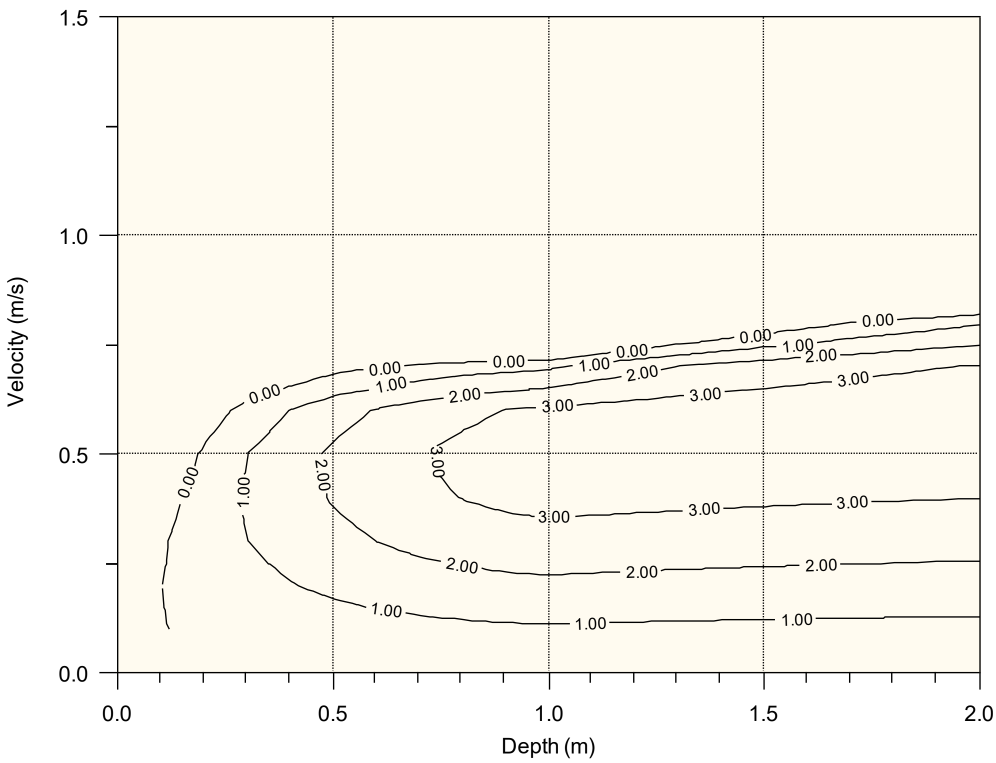


Figure 19.3 Relationship between NEI, depth and velocity for a drift concentration of 0.4 /m^3 showing the slight increase in optimum velocity with depth.

After opening SEFA, you first select the hydraulic river model, Travers in this case, then make bioenergetic predictions for the river. The zipped file is opened and you select the fish length, water temperature, roughness, and swimming loss model (Fig. 19.4). The choices are the GAMs that were saved in the zipped file. The variation in NREI with flow is shown after specifying a drift concentration.

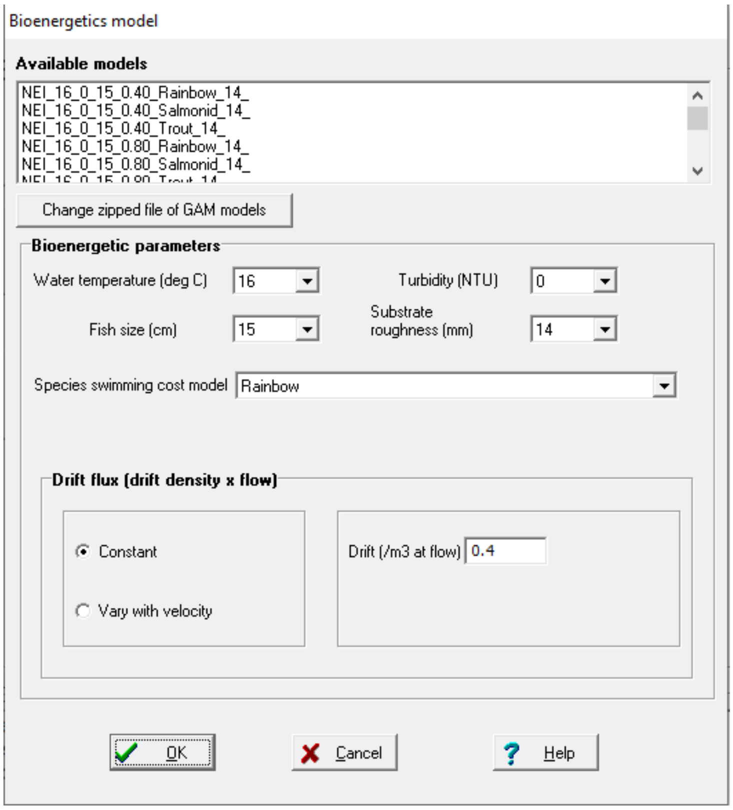
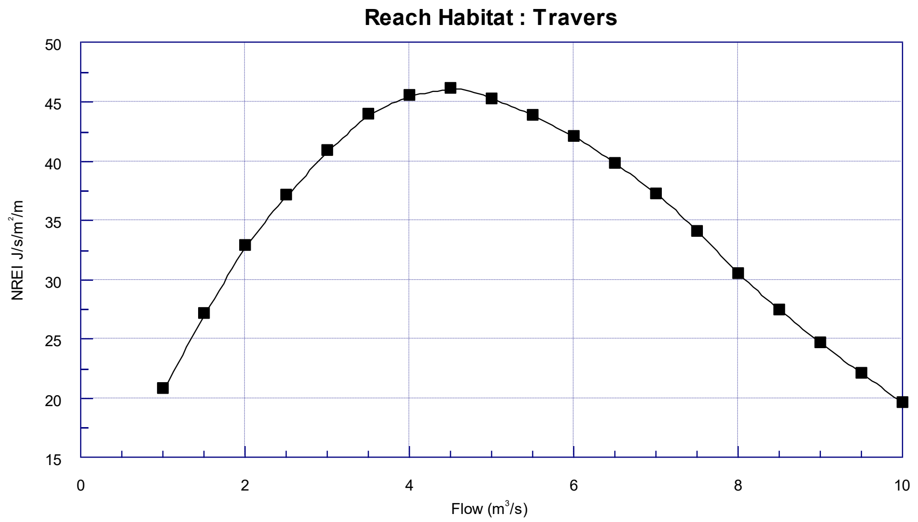
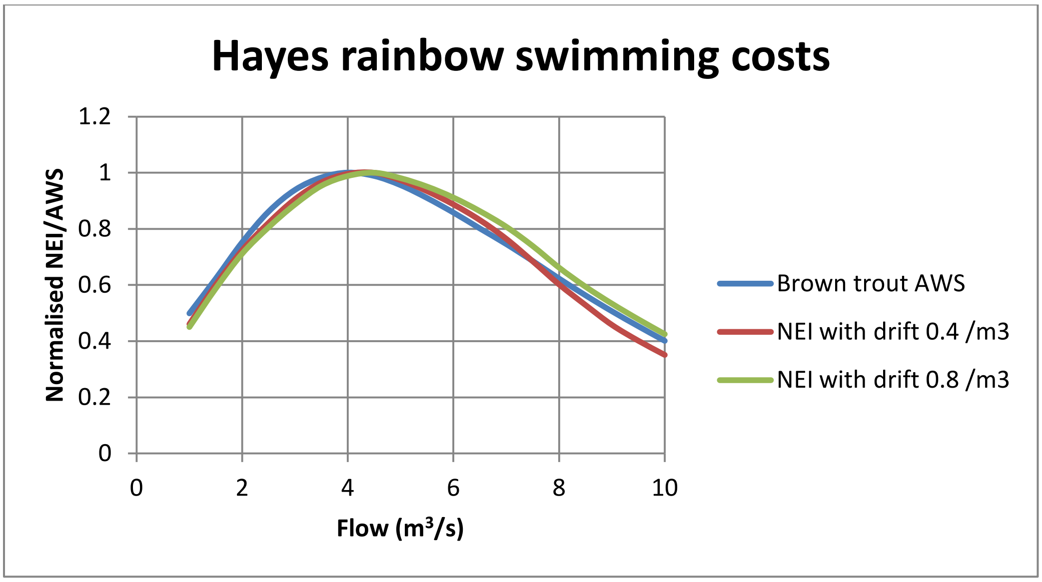


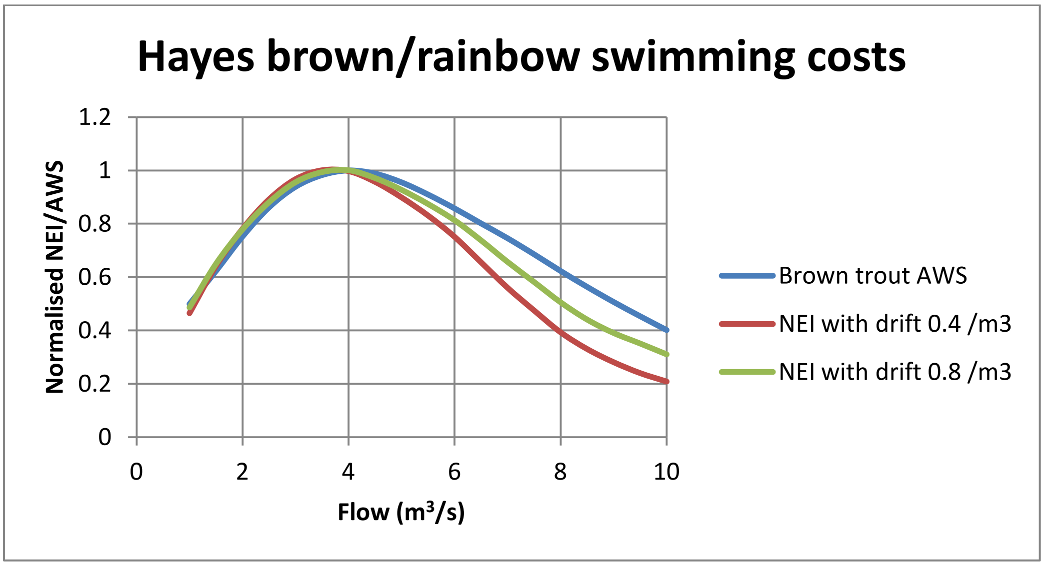
Figure 19.4 SEFA bioenergetics model dialog showing list of GAMS developed using BioenergeticsHSC and the selection boxes for parameters.

The following SEFA graph shows the relationship between NREI and flow in the Travers River.



The following two graphs compare NREI/flow relationships with AWS/flow relationship for adult brown trout using HSC based on Hayes & Jowett (1994). The NREI relationships were derived with two swimming cost models, one for rainbow trout and the other a rainbow trout model which includes some brown trout parameters. The results for two drift rates (0.4 insects per m^3 and 0.8 insects per m^3) are also shown.





19.4.3 Acknowledgement

I would like to thank John Hayes for the information and advice that he has provided for the development and understanding of the bioenergetic models. I would also like to thank John Hayes, Sean Naman, Jason Neuswanger, and Jordan Rosenfeld who made their computer code available.

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19.5 Statistical models

Statistical models can be applied to any cross-section, reach or combination of reaches.

Statistical models are used as if they are habitat suitability criteria, although they do not necessarily predict habitat suitability. Typically, a model would predict probability of use or abundance.

The two types of model that are implemented are generalized additive models (GAMs) and multiple linear regression.

Generalized additive models (Hastie & Tibshirani 1990) have been used in studies of terrestrial ecology to predict the distribution of vegetation types (Leathwick & Rogers 1996; Leathwick & Austin 2001). GAMs combine nonparametric regression and smoothing techniques with the distributional flexibility of generalized linear models. Nonparametric regression relaxes the usual assumption of linearity and shows the relationship between the independent variables and the dependent variable. Thus, GAMs are well suited to situations where there are multiple independent variables whose effect you want to model non-parametrically and where the dependent variable is not normally distributed. These models can then be applied within a river model to predict how probability of occurrence changes with flow, in the same way that habitat suitability criteria are used with a hydraulic model to predict how AWS changes with flow.

This provides an alternative approach to the development and application of habitat suitability and removes some of the subjectivity associated with the development of suitability criteria, the restrictions imposed by assumptions of a mathematical form (such as in exponential polynomial relationships), and satisfies some of the criticisms of independent habitat suitability criteria. Specifically,

- variables are not treated independently,
- interactions between variables can be considered, and
- predictions, such as probability of occurrence, are measurable.

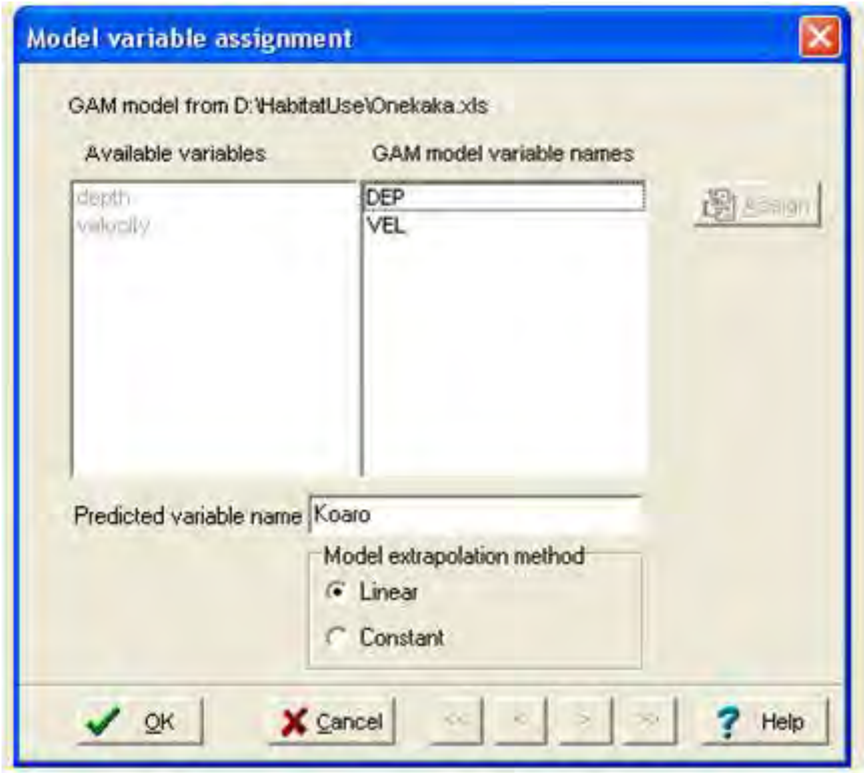
One possible form of a GAM model for habitat suitability is:

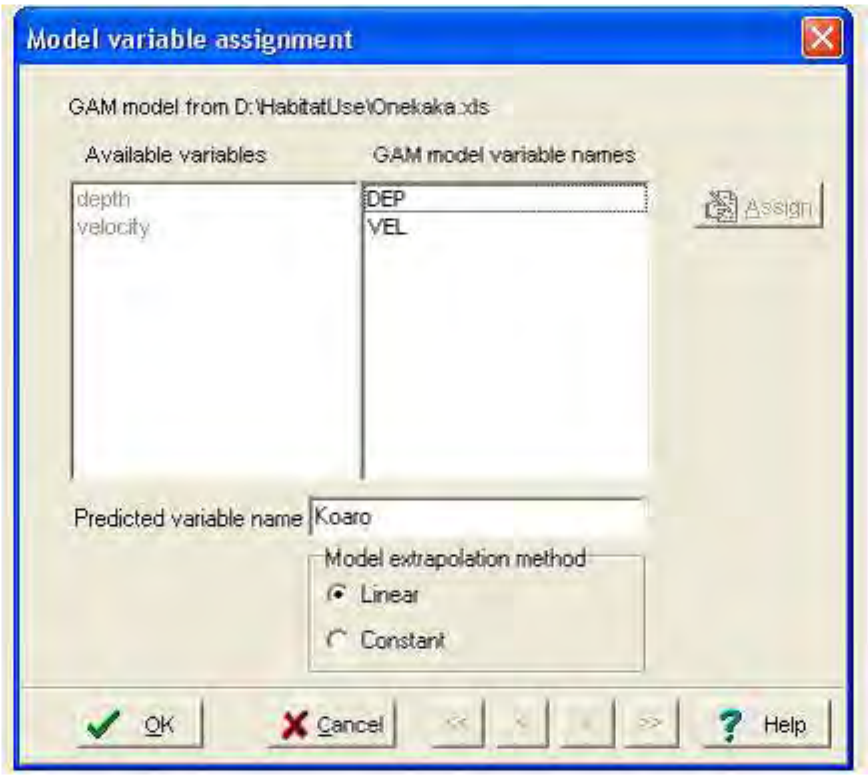
$$prediction = constant + f(d) + f(v) + f(dv)$$

where each function (e.g. $f(d)$) has a linear and non-parametric non-linear component fitted by cubic splines and the prediction is transformed into probability of occurrence using a reverse logistic transform. The degrees of freedom are constrained to give a smooth, but unconstrained, curve. Bovee et al. (1998) note that habitat selection by fish often appears to have thresholds, such as cases where a fish species does not use velocities above a certain value. The GAMs approach allows the function to adopt a shape that reflects such thresholds.

Models are selected using the menu item HSC>>Select statistical model.

The appropriate model or model library is opened. The model or library is a file of the type *.mod. This file is generated by the HABPRF or MOPED programs that are available at no cost.

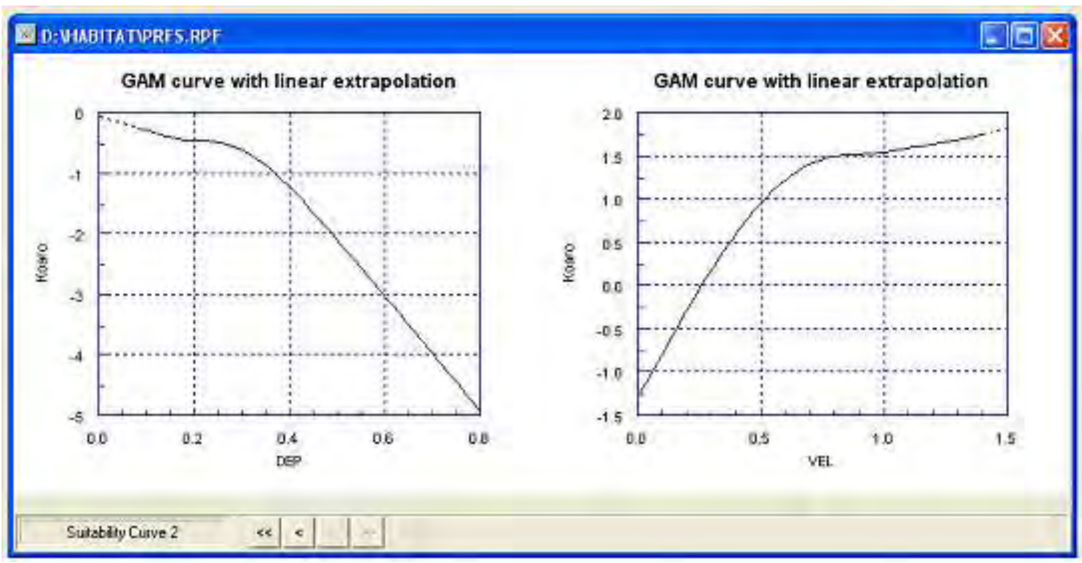




The model variables are automatically aligned with variables available in SEFA. If the variable names in the model differ from those in SEFA then the user can select (assign) which model variable to associate with the available SEFA variables.

The method of extrapolation is specified (for GAMs).

If linear extrapolation is specified, linear extrapolation using the two last model points is used whenever a SEFA variable exceeds that used in the derivation of the model. If constant extrapolation is specified the variable coefficient is held constant at the highest value. The extrapolations of the variable functions are shown as dotted lines when the functions are displayed (Select suitability curves then double click on the model).



Finally, the variable that the model predicts can be given a name.

The statistical model is then included as one of the selected suitability curves, and can be deleted when not required, like any other curve.

19.5.1 Habitat suitability and model units

The value of the model variable is predicted for each interpolated point in each cross-section for each reach. The value is summed over the cross-sections and reaches as a width-weighted and section-weighted sum. Results are presented as model units * m^2/m and model units. For example, if the model predicts abundance in number per square metre, the units would be number per metre of river and average abundance over the reach.

Habitat suitability models assign a suitability of 1 to a point where the habitat values are considered optimum. Thus, when habitat suitability values are multiplied by the area they represent and are summed, the resulting number is termed the weighted usable area or area of suitable habitat. However with logistic models, the probability of occurrence is calculated at each point and is then multiplied by the area it represents, before it is summed over the reach. In most cases, the probability of occurrence predicted by a logistic model will be considerably less than 1 and thus the equivalent of “weighted usable area” is a weighted probability of occurrence.

19.6 Multiple reaches

Data from multiple reach surveys, either of the same reach at different flows or of different reaches, can be analyzed in two ways, either by treating each survey independently (in different files) or by including all cross-section data in one reach/file. The first and simplest way is to keep each reach survey in separate files, which are then combined for habitat analysis using the 'Select reach button' in the 'Section' or the 'Reach' dialogues under 'Hydraulic Habitat’.

Alternatively, all cross-sections for all reaches could be contained in one file. If the survey flow varies between cross-sections, the appropriate survey flow must be set for each cross-section (by clicking 'Vary flow between sections' in the 'Set survey flow' dialogue under 'Hydraulic Calibration'. When analyzing reach habitat, it is possible to select the cross-sections to be analyzed using the 'Select' button in the Reach dialogues and in this way produce results for each reach or survey flow, even though the data are in one file. In both cases, cross-section data and results of analyses can be compared and then combined to produce an average result if required.

When characteristics of a multiple reaches are summed, each cross-section is weighted by the habitat weight and the total reach weight is the sum of the cross-section weights. With multiple reaches, the sum habitat weights for each reach need not sum to 1 and the weights can be used to weight reaches according to the length of river they represent. For example, if the survey was of two reaches upstream and downstream of a tributary. The reach upstream of the tributary might represent 40% of the length of river and the downstream reach might represent 60%. The sum of the habitat weights for the upstream reach would sum to 0.4 and the sum of the downstream reach weights would sum to 0.6. When the two reaches are analyzed together, the proportion of the reach modeled will be given as 100%.

If the habitat weights of two reaches each sum to 100%, each reach will be given equal weight and the proportion of the reach modeled will be given as 200%.

Multiple reaches can be selected to give the combined characteristics of a river. Different flows may be specified for each reach (and for each cross-section if the vary flows box is checked).

Results are presented in terms of the flows of the first reach specified. This is the **reference** reach.

To analyze multiple reaches, you first open (Open under the File menu) the reference reach, usually the upstream reach. Flows for this reach will be displayed on all output graphs and tables.

With this file selected as the reference reach you then select the modeling operation (e.g., model reach habitat) to display a dialogue showing the flows to be modeled, as well as three buttons labeled Reach, Section, Ratings, and Clear.

Enter the flows to be modeled in the reference reach.

To add another reach, click the reach button. By default, the flows to be analyzed will be the same as those in the previous reach. If the flows to be analyzed are changed the range of flows and interval for each reach should result in the same number of flows. For example, if flows of 0 to 10 at intervals of 1 are to be analyzed in the reference reach, and there is 2 m^3/s of tributary flow between the reference reach and the second reach, then the flows to be analyzed in the second reach will be 2 to 12 at intervals of 1.

When another reach is added, you are asked whether to combine the results of any analysis with the previous reach. If you respond YES, both reaches will be analyzed together, and the results presented for the combined reaches.

If you respond NO, the reaches will be analyzed separately, with results for each reach presented separately. To change the displays between reaches you click on the forward or backward arrows that appear on the bottom of the window.

The individual reaches will be weighted according to their total weight. Thus, if the total weights of each reach sum to 100%, then each reach will be given equal weight.

To give reaches different weights, you adjust the cross-section or transect weights so that the total for that reach is the proportion that you have determined the reach represents in the multiple reach analysis.

For example, if the first reach represents 20% of the length of the multiple reach and the second represents 80%, then individual section weights are specified so that the sum of the section weights in reach 1 is 20% and the sum of the weights in reach 2 is 80%.

If the survey type is a representative reach, then its weights will always sum to100% and thus two representative reaches would always be given equal weight. To change this, you must change the survey type to habitat mapping and set section weights to give the required reach weighting.

The clear button is used to clear the list of selected reaches and cross-sections, so that only the reference file is modeled.

Files with no substrate

If multiple files are modeled together and the first file (reference reach) contains no substrate categories, then CSI for all files will be calculated without substrate suitability. However, if the first file (reference reach) contains substrate categories and you check substrate, substrate suitability will be applied to all files. If one of the files contains no substrate categories, CSI will be calculated without substrate suitability.

19.7 Reference flow

The reference flow is the flow that is displayed on the flow axis (x-axis) of the graph or in tabulations. If the flow is the same through all reaches then the reference flow is the flow in all sections and reaches. However, if flows vary along the length of a reach, because of tributary flows or losses, or varies between reaches, the reference flow is the flow at the first cross-section of the first reach.

If flows vary between cross-sections, then the flow at the first is taken as the reference flow. The order of cross-sections can be changed by clicking on the section button and selecting sections in a different order. Highlight all sections and move them into the left-hand box. Now, in the left-hand box, highlight the section that is to be the reference flow and move it to the right-hand box. Then move across all other sections that are to be used in the simulation.

Flows in multiple channel reaches can be set individually with vary flow between sections checked. Alternatively, the flows at all sections can be set automatically by specifying the minimum and maximum flows in the main channel (the channel with the highest survey flow). Flows in minor channels are then scaled down by the ratio of their survey flow to the main channel survey flow.

19.8 Sensitivity to hydraulic variables and VDFs

The effect of depth, velocity, or substrate on habitat assessment can be determined by comparing evaluations with use depth, velocity, or substrate checked and not checked.

If use VDFs is not checked, velocities will be calculated according to the conveyance of the compartment. This can be used to test the sensitivity of calculations to the predicted velocity distribution.

The following variables are calculated for each flow:

- Depth

- Velocity
- Width
- Wetted perimeter
- Froude number
- Pool, run, riffle habitat
- and the specified habitat criteria.

Velocity is calculated as an area weighted average i.e.,

Sum(V x dA)/Sum(dA)

19.9 Confidence limits

Confidence limits can be placed on AWS predictions. Estimates of confidence limits are based on the assumption that cross-section locations are selected randomly and the bootstrapping method selects random combinations of cross-sections to calculate AWS and thus variability. These statistical confidence limits reflect the variability in cross-section properties and do not address all uncertainties in instream habitat modeling.

In the randomization process, cross-sections are selected with replacement, so that in the extreme case, a bootstrapped reach could be made up from only one cross-section. If the river is comprised of pools, riffles and runs and cross-sections are selected to represent these habitat types, the assumption of random selection of cross-sections is invalid. However, it is possible in bootstrapping to randomly select cross-sections within each of the habitat types and this is the procedure used in SEFA.

With stratified random sampling, the mean value is calculated as the weighted average over all habitat types.

$$\bar{x} = \sum_{i=1}^{m} w_i x_i$$

Where $\bar{x}$ is the overall reach mean, w_i the weight applied to habitat type i, and xi is the mean of cross-section values in habitat type i in a reach of m habitat types. The weight wi is the proportion of river reach length represented by that habitat type, so that the sum of the weights over the reach equals 1. Individual cross-section weights within each habitat type are equal and their sum equals w_i.

The variance (s^2) of habitat weighted estimates is:

$$s^2 = \frac{V_1}{V_1^2 - V_2} \sum_{i=1}^{N} w_i \left(x_i - \mu^*\right)^2 ,$$

Where V_1 is the sum of the weights, V_2 is the sum of the squares of the weights, w_i is the habitat type weight, xi is the randomly selected variable, u* the habitat type mean for xi.

The standard deviation is the square root of s^2, and the standard error (SE) is the standard deviation divided by the square root of the number of cross-sections.

Confidence limits for the overall mean are:

$$CL_{mean} = \bar{x} \pm s^2 t_{[\alpha, n-1]}$$

Where t is the t-statistic for the whole sample (n cross-sections) calculated by the bootstrap-t method described by Manly (1997), i.e., the departures from the observed means are summed over the habitat types:
Sum((x*-u*)*wi)/sum(wi) where x* is the bootstrap mean for the habitat type, u* the habitat type mean, wi the weight for the habitat type. This is divided by the standard error to get the t value.

These confidence limits indicate the confidence that can be placed on the value at a particular flow, assuming that cross-sections have been randomly selected within each stratum. In practice, selection within a stratum tries to encompass the range of variation within the stratum thus reducing the uncertainty that would be associated with truly random sampling.

Confidence limits can be displayed by clicking on the graph options icon. The default limits are the 67% confidence limits and this value can be changed in the graph display options.

Confidence limits are calculated by bootstrapping in reaches where cross-sections have been randomly chosen. Bootstrapping assumes that any combination of cross-sections could be chosen and that combination is randomly selected with replacement.

The cross-section weights (as determined by habitat mapping) are used to determine the combinations of cross-sections are randomly selected. For example, if there are 6 run, 6 riffle, and 6 pool cross-sections, AWS will be calculated for 6 randomly selected run cross-sections, 6 riffle cross-sections, and 6 pool cross-sections. It is assumed that the cross-section weights for each of the habitat types are different. If they are the same, it will be assumed that they represent the same habitat type.

Two types of confidence limits can be displayed:

confidence limit on the values, or

confidence limit on the shape of the curve.

Confidence limits on value

Vertical error bars are plotted on the AWS values. This is the "minimum" confidence limit that the AWS value lies within the range. It is a "minimum" because there are other factors that may also influence the accuracy of the AWS value.

The method of calculating confidence limits on the values is the bootstrap-t method of Efron, as described by Manly in “Randomization, bootstrap and Monte Carlo methods in biology”, Chapman and Hall 2^{nd} edition 1997.

In evaluation of flow requirements, the shape of the curve is of more interest than the actual amount of habitat, and as the examples show, fewer cross-sections are needed to define the shape than are needed to quantify the amount of habitat.

Confidence limits on shape of curve

In assessing the effect of flow changes, the shape of the curve is often more relevant than the value and flow recommendations are often based on maxima or breakpoints where there is a sharp change in the slope of the graph. The curve confidence limits help indicate the confidence that we can in maxima or points where there is a change of grade.

For example, the flow that provides maximum habitat is often of interest. The confidence limits on the curve will show the confidence limits on the flow that provides maximum habitat. To do this, the program, runs 1000 simulations with cross-sections selected randomly, and examines the shape (slope) of the flow relationships. Because the slope of the relationship is 0 at the maximum values, we can calculate the confidence limits around this slope. This procedure is carried out for all points on the graph.

No confidence limits are plotted when there is some uncertainty about the limits. This occurs when the confidence interval is low and when the cross-section data are skewed, and the actual mean value may not be within the confidence interval.

Where the graph has little curvature, the confidence limits on the slope will be wide, but these points are usually of little interest in the assessment of breakpoint and maxima reliability.

A graph can be plotted to show the slope confidence intervals in terms of slope (m^2/m per m^3/s or ft^2/ft per cfs for AWS) versus flow. Figure 1 shows the calculated relationship between flow and slope and the upper and lower bounds on that relationship. At the flow Q1, QL and QU indicate the confidence limits on the slope at Q1. If Q1 has a slope of zero (the maxima), then we can be confident that the maxima lies between QL and QU.

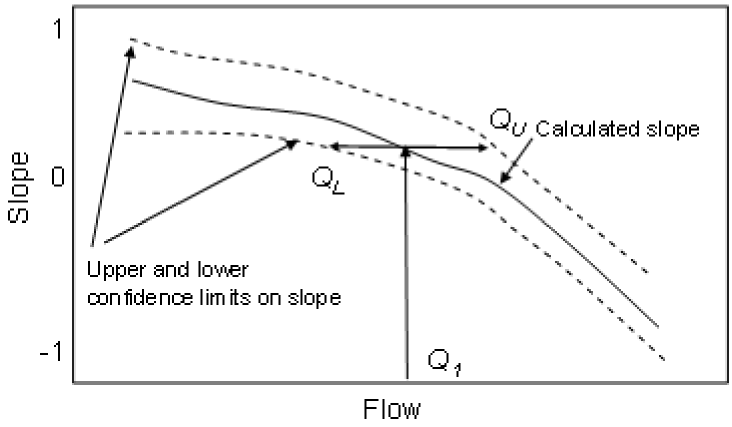


Figure 1. Relationships between slope of habitat/flow relationships and flow and an example of determining the confidence limits on flows.

Representative reach

Confidence limits on representative reach surveys are calculated as if each cross-section has equal weight, and thus is equally likely to be randomly selected. This is incorrect, of course, and the confidence limits on a representative reach will be wider than the true confidence limits (that are impossible to define from one representative reach).

19.10 Modeling the effect of flow fluctuations on habitat

The evaluation of flow fluctuations involves comparing habitat at a range of flows with habitat at a base flow. The amount of usable habitat under a flow fluctuation is the minimum amount of habitat at a particular location over the fluctuation range.

The concept is that some aquatic species may become established at locations that provide suitable habitat at base flow. If the flows change, and the location no longer provides suitable habitat, then that location would not be considered suitable under a fluctuating flow regime.

This assumes that the species is unable to move to other suitable habitats.

The numerical evaluation of habitat suitability is to sum the available habitat over a reach, assuming that the habitat value of a location is the minimum of the habitat at the low point of the flow fluctuation, at the high point of the fluctuation, or the habitat at base flow.

Thus, at each simulated flow, the amount of suitable habitat is the amount of habitat that overlaps in space the suitable locations that were available at base flow.

There are four steps to simulating habitat suitability over a range of fluctuating flows. The first three are common to all flow simulation procedures, i.e.,

- Select ratings
- Select habitat suitability curves
- Select range of flows
- select the base flow
- select the number of steps within the flow fluctuation range

For example, if the flow variation is 10 to 20 and the baseflow (normal flow) is 15 with 5 steps is 10. For the full fluctuation i.e., fluctuating from 15 down to 10 and from 15 up to 20, the amount of habitat at each point is the minimum of AWS at 15, AWS at 10, AWS at 20.

Results are presented as the amount of habitat at each flow over the fluctuation range and as a summary showing the habitat loss caused by the proportions of the fluctuation.

Proportion of maximum fluctuation	**Loss (AWS m^2/m)**	**% Loss of AWS at base flow**
0.0	0.000	0.000
0.1	0.703	13.670
0.2	1.255	24.387
0.3	1.711	33.267
0.4	2.131	41.428
0.5	2.535	49.276
0.6	2.894	56.246
0.7	3.194	62.086
0.8	3.448	67.014
0.9	3.687	71.674
1.0	3.927	76.330

Another example of a flow fluctuation might be a flow of 2 increasing frequently to a flow of 12. To find out how much AWS is lost with this fluctuation, you would enter:

Minimum 2

Maximum 12

Steps 5

Baseflow 2

The result would be calculated for 5 fluctuations; 2 to 12, 2-10. 2-8, 2-6 and 2-4.

The text output is 3 tables, the last being the same output that you would get from a reach analysis without flow fluctuation.

Flow (m^3/s)	AWS with fluctuation (m^2/m)	% of AWS at baseflow
2.00	2.24	44.71
2.00	2.56	51.04
2.00	2.96	59.07
2.00	3.46	69.16
2.00	4.16	83.03
2.00	5.01	100.00
4.00	4.16	83.03
6.00	3.46	69.16
8.00	2.96	59.07
10.00	2.56	51.04
12.00	2.24	44.71

The second table lists a summary of the fluctuations. The maximum fluctuation that was specified was 10, so with the maximum fluctuation (2 to 12), there is 55% loss of AWS. With no fluctuation (the first row) there is no loss of AWS.

Area Weighted Suitability loss with flow fluctuations for: Deleatidium (mayfly) (Jowett et al. 1991)

Proportion of maximum fluctuation	Loss (AWS m^2/m)	% Loss of AWS at baseflow
0.00	0.00	0.00
0.20	0.85	16.96
0.40	1.54	30.83
0.60	2.05	40.92
0.80	2.45	48.95
1.00	2.77	55.28

19.11 Fish passage

The width of river that provides suitable water depths and velocities for the passage of fish or boats can be calculated for the reach, either at the surveyed flow or for simulated flows.

Results are presented as the contiguous width where this is the maximum width in a cross-section with the required minimum depth and velocity. The total width is the sum of all the elements of the cross-section that meet the specified criteria.

The flow that provides a minimum depth can be found by setting the allowable passage velocity to a high value, and similarly, the flow that provides a minimum velocity can be found by setting the allowable passage depth to zero.

The minimum passage width for the reach is the minimum of all the cross-sections.

Wetted widths are listed, as is the wetted width at the section with the minimum contiguous width. This allows the % of river channel available for passage to be calculated.

19.12 Standard Setting

Standard setting methods are used to determine minimum flow requirements, and allow the selection of a minimum flow that meets the required standard.

19.12.1 Habitat retention

Habitat retention is often used to set minimum flows. For example, retention of 90-100% of habitat at the index flow provides a degree of protection applicable in streams and rivers where the species or instream use is highly valued, whereas 60-70% habitat retention might be a standard applicable to rivers containing a less valued species or instream use.

The index flow is typically the mean annual low flow (the minimum flow that occurs every 2 years or so). The mean annual low flow is used as the index flow because it is often assumed that low flows that occur every year or two might be limiting the abundance of long-lived species.

The retention analysis determines flows that provide varying standards of protection (habitat retention). This is expressed as a percentage of the habitat (AWS) available at the index flow, typically the mean annual low flow.

The analysis also calculates AWS up to the maximum flow (specified by user) and determines the flow that provides maximum habitat (AWS).

19.12.2 Tenant method

The Tennant method was originally called the 'Montana Method' because the approach to calculating an instream flow requirement was developed by Don Tennant (1976[7]) for use in Montana and Wyoming and was used by the Montana Fish and Game Department. The 1972 version of the Montana Method used three percentages of the annual flow as alternative levels of stream habitat quality. In response to a question on how the percentages were determined Tennant made the following comment:

> Well, I arrived at them just, from a lot of experience looking at different flows and what I felt were good flows. I always like to look at a 10% because I think that's a danger to most any stream I've seen. When you get 10% or below you're in serious trouble. It's a short-term survival habitat situation usually, at

[7] Tennant, D. L. 1976: Instream flow regimens for fish, wildlife, recreation, and related environmental resources. In: Orsborn, J. F; Allman, C. H. eds., Proceedings of the symposium and speciality conference on instream flow needs II. American Fisheries Society, Bethesda, Maryland. Pp. 359-373.
Tennant, D.L. (1976). Instream flow regimens for fish., wildlife., recreation and related environmental resources. Fisheries Vol. 1, No.4: 6-10.

best, and I color it red because I see red when I observe a flow less than that and a third always looks like a pretty good flow and two-thirds always looked real good, but instead of using 33.333 and 66-2/3, I rounded it off at 30% and 60%.

Between 1972 and 1975 Tennant continued his studies by studying 10 streams in 3 US states (mostly in Montana and Wyoming) and refined the % of mean flow required to maintain those streams in states of well-being varying from degraded to excellent. The refined criteria are:

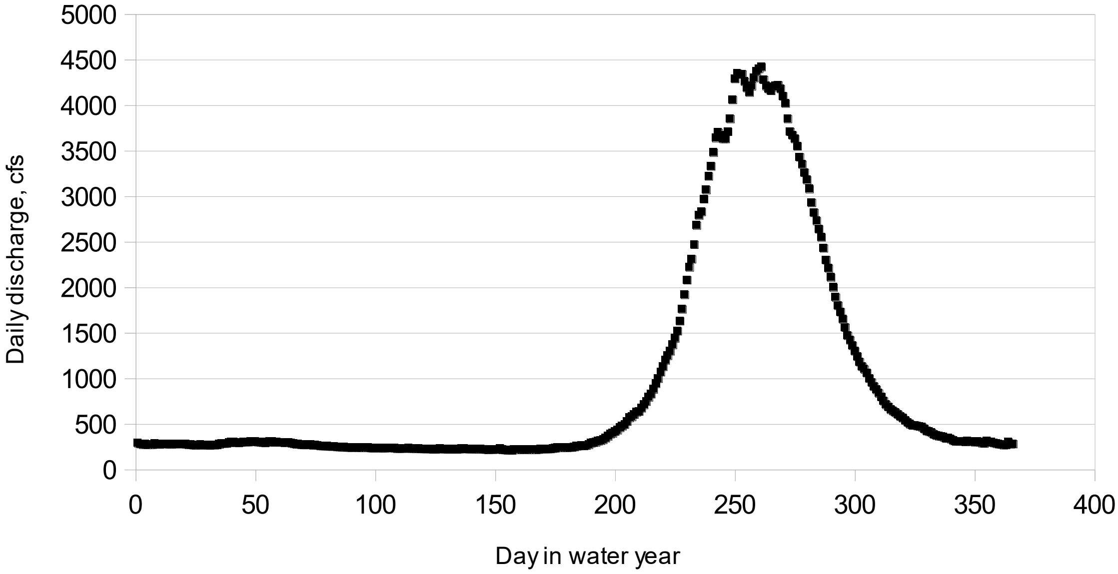
Maintenance standard	Percentage of Mean Annual Flow	
	Winter Season (low flow season in Montana)	Summer Season (high flow season in Montana)
Optimum range	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	<10	<10

SEFA calculates the mean flow from the imported flow record and presents Tennant's recommended flow regimens.

Tennant considered that width, depth, and velocity were physical instream flow parameters vital to the well-being of aquatic organisms and their habitat. Tennant also believed that 10% of the mean flow was a minimum short-term survival flow at best and that this was associated with a wetted width of 60% of mean flow width, an average depth of 1 foot, and an average velocity of 0.75 fps. He considered that average depths from 1.5 to 2 feet, and average velocities from 1.5 to 2 fps were in the good to optimum range.

The problem with the Tennant (or Montana) method is that the percentages of mean flow and the resulting depths, velocities and widths will only apply to rivers that are similar in morphology to his group of 10 study streams. It is worth looking at a typical hydrograph for a stream in Montana (Clarks Fork Yellowstone River at the USGS gaging station near Belfry, Montana). The period of record is from 1921-2016.

The two time periods used by Tennant are from October - March (Winter) and from April – September (Summer) with 1 October as the beginning of the water year.



Daily average discharges for the Clarks Fork Yellowstone River near Belfry Montana. The mean annual discharge is 939 cfs for the period of record from 1921-2015. (The last day of March, i.e. winter, is day 184.).

It should be noted that although you can change the start of the water year, the Tennant method uses only the average of the annual flows. The average annual discharge will be essentially the same no matter what starting month is used.

SEFA provides an alternative method of evaluating flow requirements according to Tennant's habitat criteria. The Hydraulic habitat>>Standard setting>>Tennant analysis in SEFA can be used with river survey data to determine the variation in depth, velocity and width with flow and to determine the flows that meet Tennant's standards of well-being for depth, velocity and width. Tennant’s standards for well-being for depth, velocity and width are:

Sustain short-term survival	Depth >= 1 foot, velocity >= 0.75 fps, wetted width of 60%
Good survival	Depth >= 1.5 feet, velocity >= 1.5 fps, wetted width 75%
Excellent to outstanding	Depth >= 2 feet, velocity >= 2 fps, wetted width 90%

The Hydraulic habitat>>Standard setting>>Tennant analysis shows Tennant’s standards of well-being (short-term survival, good survival and excellent survival) on a graph of depth, velocity and % width at mean flow versus % of mean flow. The text output also lists depth, velocity and % width at mean flow for flows of 10-100% of mean flow.

The results are environmental flows based on Tennant velocity and depth criteria, whereas the Tennant (Montana) method calculates environmental flows based on the percentages of average annual discharges. The environmental flows calculated using the Tennant Method will not necessarily be the same as the environmental flows calculated using the Tennant criteria for velocity and depth.

20 Time Series Analysis

20.1 Units of time series files

SEFA provides a flexible system for time series analyses. The units of variables in time series files can be either metric (m^3/s), feet (cfs) or other (no conversion). The results of analyzing metric or feet data are displayed in the selected display units (feet or metric). If other units are specified, no conversion is applied regardless of display units. This allows analysis of data other than flow data. However, some analyses (riparian and AWS) do require flow data and the other unit choice is not allowed for these procedures.

Data in the time series file is analyzed item by item, so that values are not necessarily daily mean values. For example, the seasonal analysis procedure can be used to analyze sporadic measurements of water quality. The analysis of indicators of hydrologic alteration (IHA) is the only procedure that expects daily mean values. If IHA data are not a complete series of daily values, missing values can either be interpolated or considered as missing. If the option to interpolate missing values in the IHA is not checked, then monthly values with missing values are marked with an asterisk.

20.2 Select AWS/Flow relationship

The first dialogue displays a list of the AWS/Flow relationships that were last calculated for the open rhbx file. If no file has been opened, or no AWS/Flow relationships have been saved in the open file, a blank second dialogue will be displayed. If you press the Import from File button, you can either import an AWS/Flow relationship from a SEFA file or a text (csv, xls*) file. If the first dialogue displays the AWS/Flow relationships that have been saved in the open SEFA, and you wish to use other relationships, press the Cancel button and a blank second dialogue will be displayed, allowing you to import relationships from another file.

Any of the listed relationships can be selected and saved. When selected the values will be shown in the table and a graph of the relationship is displayed. When the relationship is saved (after setting methods of extrapolation), the graph, table and selection box is cleared and the saved relationship is shown in the saved list. Relationships that have been saved can be deleted by selecting them in the saved list and pressing the delete button.

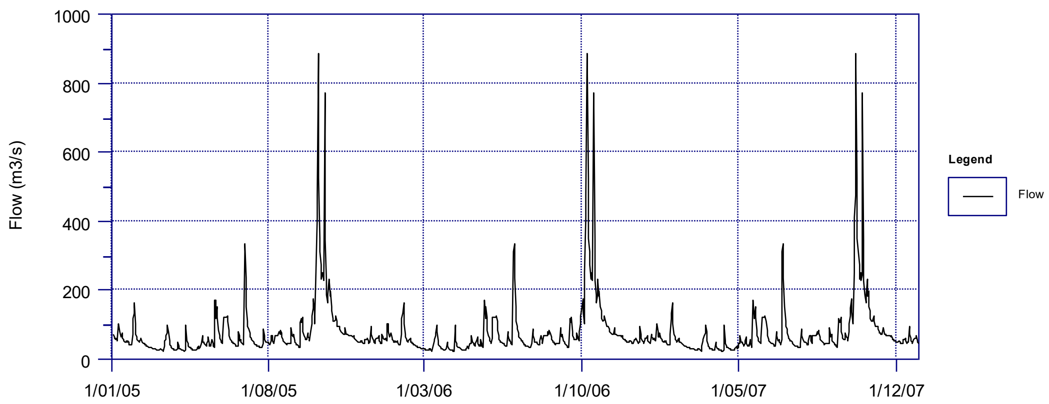
Extrapolation above and below the maximum and minimum flows in the AWS relationship can be set as the flow value at which AWS becomes zero. For low flows, the AWS at zero flow can be specified and for high flows, a constant value (last value in the relationship) can be used. The default extrapolation is that the flow values for zero AWS are calculated by linear extrapolation of the first or last three pairs of values.

Any AWS/Flow relationship, either an existing SEFA file in which the relationship(s) have been saved or a text file with pairs of flow and AWS values and width as text, can be imported by clicking the Import from file button.

20.3 View flow or AWS series

This procedure allows you to display one or more variables selected from the imported flow series file graphically. If the file contains a valid date variable, the selected variables are plotted with the date on the X-axis. If no date variable is contained in the file, the selected variables are plotted as if each variable is a daily value.

The graph of AWS requires that a relationship between flow and AWS be selected. This relationship is used to transform the flow variable into AWS.



As with any graph, it can be altered by selecting graph options. 

20.4 Seasonal flow and AWS statistics

This procedure calculates statistics for either flow or AWS either by season or by year and season. The calculation does not treat the data as a time series by weighting the value by the time it represents. Instead each data value is treated as an independent sample. For example, the overall mean is simply the average of all values for that variable.

The calculation of AWS statistics requires that a relationship between flow and AWS be selected before carrying out the analysis. This relationship is used to transform the flow variable into AWS.

If the data file contains only one date variable that variable is selected automatically for this analysis. If there are two or more date variables, those variables are listed and one must be chosen.

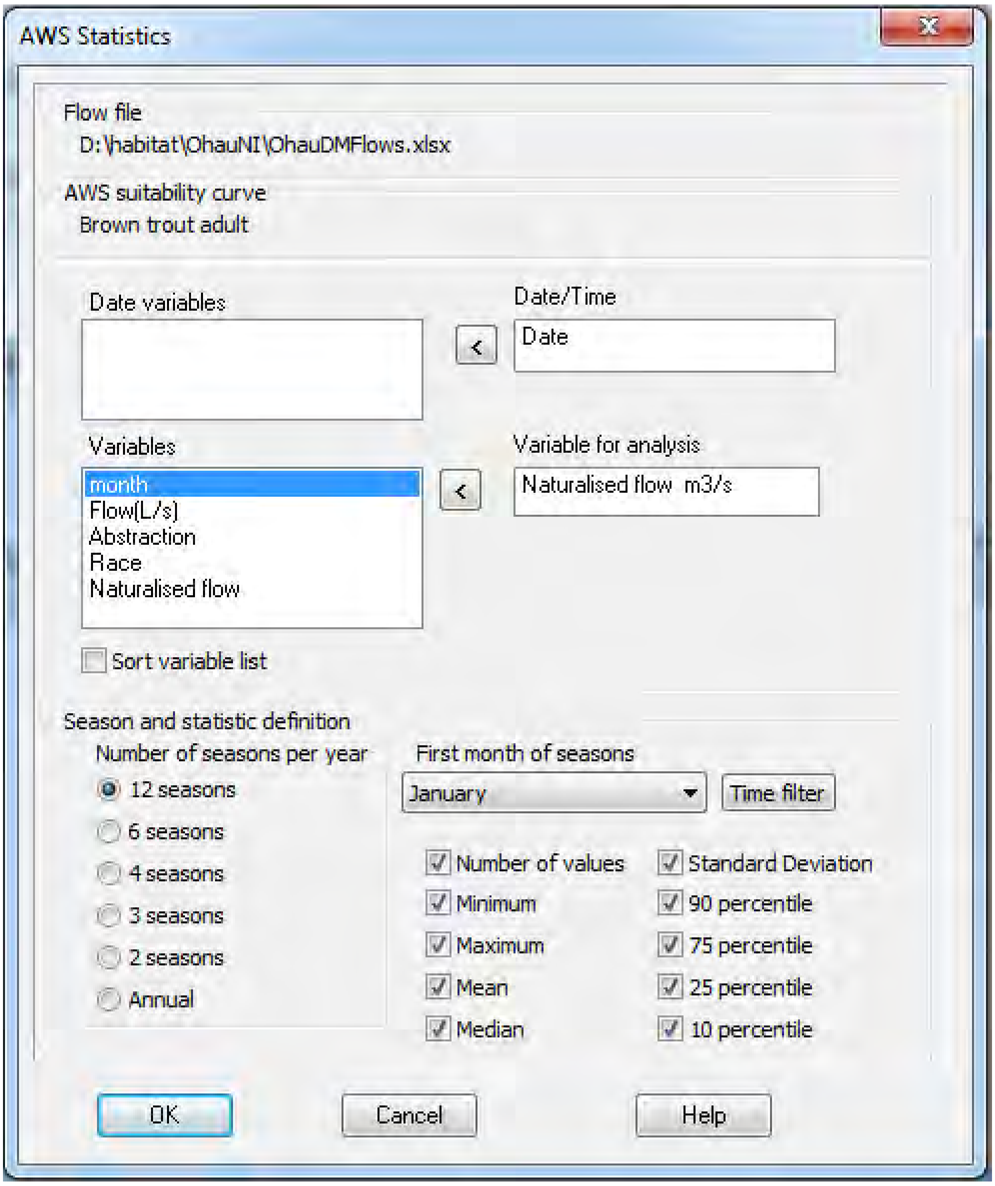
The variable to analyze must be selected, as well as the statistics to be produced. These are:

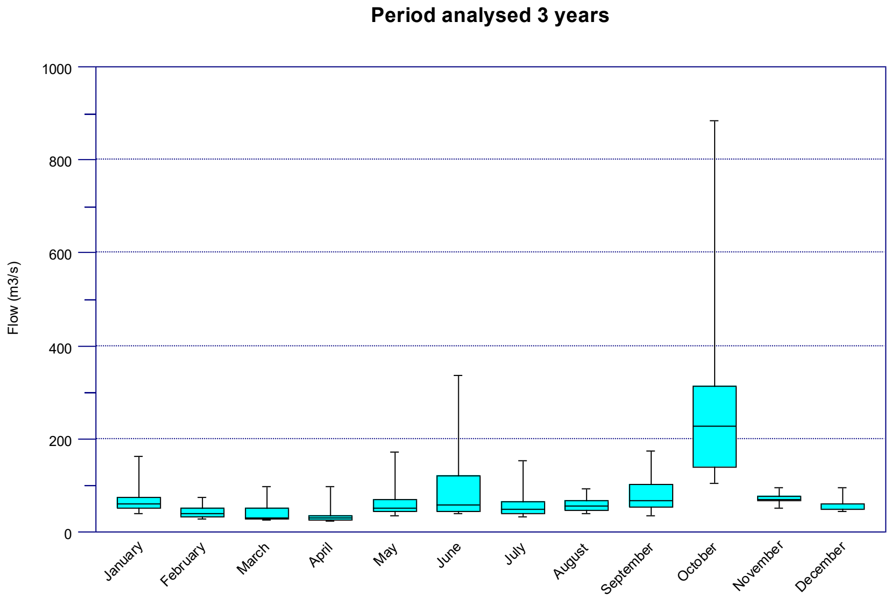
- Minimum
- Maximum
- Mean
- Median
- Standard deviation (denom. n-1)
- 10 percentile
- 25 percentile
- 75 percentile
- 90 percentile

The standard deviation is calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})}{n-1}}$$

If there is only one value, the standard deviation is given as zero.





The box and whiskers graph shows the “box” with the mean value surrounded by the 25 and 75 percentiles, with the extremes as the “whiskers”,

The statistics of all selected variables can be listed in tables obtained by selecting Show as text after the graph is displayed. These tables can be copied to the clipboard and pasted into Excel or similar programs.

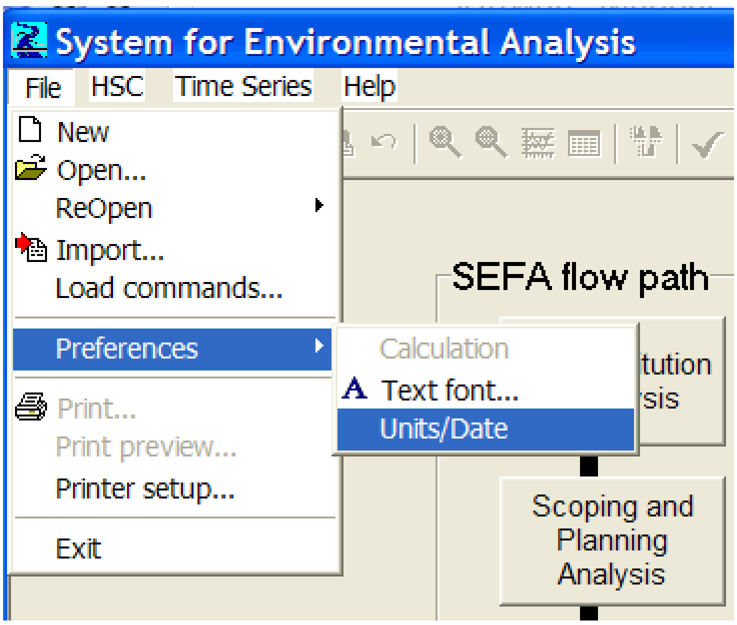
Incomplete years or months are not marked, but the user can see whether the correct number of values are in each season by displaying the sample size.

The following table is the annual seasonal statistics for 1 variable (Flow) for 2 seasons.

Statistics for Flow from file: E:\Riohabsim\Example_data\Flow_data_example_3Years.xls

Year/Season	Jan - Jun	Jul - Dec
Sample size		
2005	181	184
2006	181	184
2007	181	184
Minimum		
2005	23.740	32.970
2006	23.740	32.970
2007	23.740	32.970
Maximum		
2005	335.601	884.916
2006	335.601	884.916
2007	335.601	884.916
Mean		
2005	57.442	97.299
2006	57.442	97.299
2007	57.442	97.299
25% exceedence		

The number of decimals displayed can be altered using the File>>Preferences>>UnitsDate.



20.5 Indicators of hydrologic alteration

A series of hydrological statistics are calculated from the imported flow file. The file is expected to contain a date and one or more daily mean flows.

The monthly analyses are based on calendar months.

The indicators of hydrologic alteration are a set of hydrological statistics and indices, largely based on a paper by Poff (1996).

The calculation of IHA uses the imported flow series.

Flow statistics are calculated for calendar months and water years specified by the starting month. For example, February mean flows in a leap year will be the arithmetic average of 29 values. Annual flow statistics are based on the year of data and moving means do not overlap into preceding or following years.

Most statistics are self-explanatory, but some may be unfamiliar to users.

Zero days is the number of days with zero flow.

The base flow index is the annual 7-day minimum flow divided by the mean annual flow

The median rates of rise and fall are medians of all positive or negative changes in flow. Zero flow changes are ignored.

A reversal occurs when the flow on a day is less than the previous day and less than the next day or when the flow on a day is greater than the previous day and greater than the next day

The coefficient of variation is the standard deviation divided by the mean flow.

The coefficient of dispersion is the difference between the 75 and 25 percentiles divided by the median flow.

High flows are flows that exceed the 75 percentile. Low flows are flows less than or equal to the median (50 percentile). Flows between 50 and 75 percentiles are considered as recession. A high event begins when the flow exceeds the 75 percentile or when the flow is in the recession range and the flow increase is greater than 25% (i.e., (Q2-Q1)/Q1 > 0.25). A high flow event ends when the flow falls below the median flow or when the flow is in the recession range and the rate of flow decrease is less than 10% (i.e., Q1-Q2)/Q1 < 0.10. A low flow event begins when the flow falls below the median flow.

The average length of an event is the total number of days of high or low flow divided by the number of events.

Fre3

Fre3 is an index of flood frequency that is used in New Zealand. It is the frequency of floods exceed 3 times the median flow. Three times the median flow not usually large enough mobilize bed material, but it does act as a flushing flow. Clausen & Biggs (1997) considered that it was the most ecological useful overall flow variable in New Zealand streams because it explained a significant amount of the variance in four out of the six main benthic community measures. Periphyton biomass decreased with increasing Fre3 ("a rolling stone gathers no moss"), whereas invertebrate density had an increasing/curvilinear relationship with Fre3 - the intermediate disturbance hypothesis. Periphyton species richness and diversity decreased with increasing Fre3. A flood is whenever the daily mean flow exceeds 3 times the median and the flood ends when there have been 5 or more consecutive days below 3 times the median.

Richards-Baker Index

The Richards-Baker index (R-B Index) is an index of flashiness and is closely related to FRE3 and the coefficient of variation. It is calculated from daily values as the sum of the absolute daily differences ∑abs(Q(i)-Q(i-1)) divided by the sum of the daily values ∑Q(i).

According to Baker et al (2004) the index integrates several flow regime characteristics associated with the concept of stream flashiness. The index is positively correlated with increasing frequency and magnitude of storm events, and negatively correlated with baseflow and watershed area.

• The size of the R-B Index varies greatly among ecoregions of six US states, suggesting that some of the physical attributes of the landscape that result in distinct ecoregions also impact stream flashiness.

• The R-B Index has lower interannual variability than many other flow regime indicators, making it well suited for detecting gradual changes in flow regimes associated with changes in land use and in land management practices.

• The R-B Index may be useful as a tool for assessing the effectiveness of programs aimed at restoring more natural streamflow regimes, particularly where modified regimes are a consequence of land use/land management practices.

Colwell indices

The indices of constancy and predictability are calculated from daily mean flows using the method of Colwell (1974), using 11 classes (states) of flow division based on a logarithmic scale to the base 2, ranging from < 0.125 times the mean flow to > 64 times the overall mean flow. The 10 flow divisions are at intervals of 2^(i-4) times the overall mean flow, where i increases from 1 to 10.

The following two paragraphs are modified from Colwell (1974).

The pattern is maximally predictable if a variable has the very same seasonal pattern in all years. The pattern is designated minimally predictable if all states are equally likely in all *time steps (i.e. seasons), so that nothing can be predicted about the state of a variable based on the season.*

Predictability (P) has two separable components, constancy (C) and contingency (M) (i.e., P = C + M). Maximum predictability can be attained as a consequence of either complete constancy, complete contingency, or a combination of constancy and contingency, with respect to time. In the case of complete constancy, the state is the same for all seasons in all years. In the case of complete contingency, the state is different for each season, but the pattern is the same for all years. A pattern invariant for all years, but with some states characteristic of more than one season is also completely predictable, but its predictability has partial contributions from both constancy and contingency.

From a hydrological point of view, constancy (C) is a measure of the variability within a year. Predictability (P) is a measure of the variability between years.

Missing values

If there is missing data, the gaps can be either filled automatically by linear interpolation or can be considered missing data on the output. If the option to interpolate missing values in the IHA is not checked, then monthly values with missing values are marked with an asterisk. Flow data are not extrapolated so that the first and last years may be incomplete.

Warning - If multiple variables are being analyzed then a missing value in any of the selected variables will result in all variables for that date to be ignored.

References

Baker D.B., Richards R.P., Loftus T.T., Kramer J.W.,(2004). A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association 40(2):503-522.

Beissinger, Steven. 1986. Demography, Environmental Uncertainty, and the Evolution of Mate Desertion in the Snail Kite. Ecology, Vol. 67, No. 6. (Dec., 1986), pp. 1445-1459.

Clausen, B.; Biggs, B.J.F. (1997). Relationships between benthic biota and hydrological indices in New Zealand streams. Freshwater Biology 38: 327-342.

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Inger, Robert F. and Robert K. Colwell. 1977. Organization of Contiguous Communities of Amphibians and Reptiles in Thailand. Ecological Monographs, Vol. 47, No. 3. (Summer, 1977), pp. 229-253.

Poff, N.L.; Ward, J.V. (1989). Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46: 1805-1817.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10: 1163-1174.

Stearns, S.C. (1981) On measuring fluctuating environments: predictability, constancy and contingency. Ecology, 62, 185-199.

20.6 Riparian inundation analysis

Riparian modeling usually considers the frequency, timing and duration of inundation flows. This procedure calculates the total number of days (or number of inundation events i.e. contiguous days of inundation) by season.

Inundation is referenced to the water level at some flow, termed the base flow. The base flow would normally be a reasonably high flow, such as the mean flow. The inundation level is specified as the height above the water level at base flow.

The data files required for this analysis are a river model (with good high stage, stage discharge relationships) and an imported file of flows and dates. The rating curves (stage-discharge relationships) river model should be accurate up to the inundation height. For multi-channel reaches, particular note should be given to the specification of the channels, with vertical walls between channels as appropriate and rating curves that predict the same water level when channels coalesce. Section 5.4 describes these requirements in more detail.

The analysis produces a table showing the relationships between flow and water height above base flow for each cross-section and for the whole reach. The table also shows the area that is inundated.

Another table gives the number of days or number of inundation events by season and by year.

SEFA 28/10/2011

File: E:\Riohabsim\Example_data\Flow_data_example_3Years.xls

Inundation Analysis

Inundation criteria used:

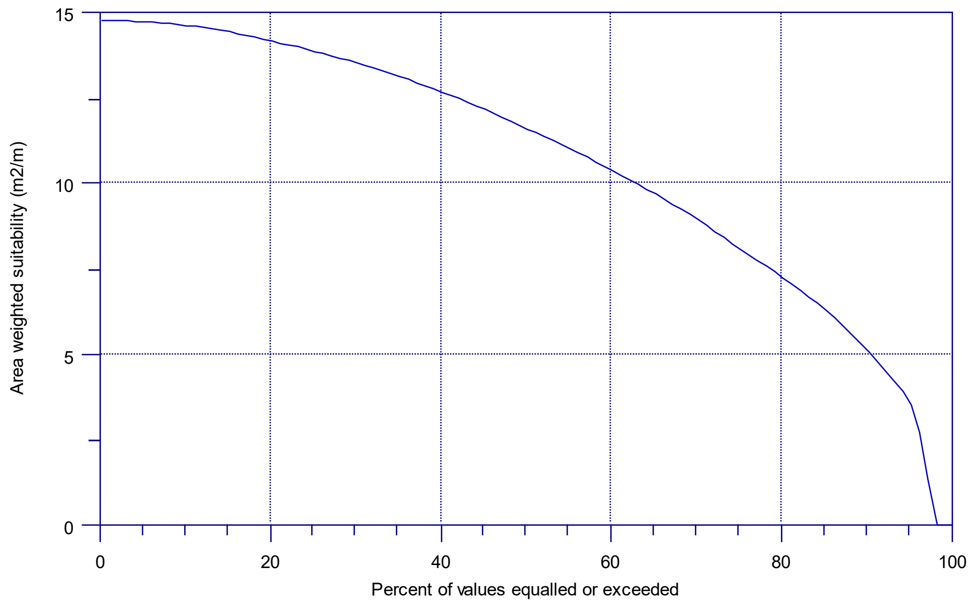
Minimum inundation flow (base flow) = 12 m^3/s

Event : Inundation height above base flow > 1 m

Year season begins	Number of days event occurred											
	January	February	March	April	May	June	July	August	September	October	November	December
2005	3	0	0	0	6	8	1	0	5	26	0	0
2006	3	0	0	0	6	8	1	0	5	26	0	0
2007	3	0	0	0	6	8	1	0	5	26	0	0

20.7 AWS duration analysis

As with the seasonal analysis of AWS, this procedure requires the selection of a relationship between AWS and flow and a file of flow values. The flow values are transformed into a series of AWS values which are analyzed to show the frequency with which the AWS values are exceeded. This is the AWS equivalent of a flow duration curve.



A table is also produced with the statistics of the AWS series (mean, median, extremes and a percentiles).

AWS (m^2/m) statistics for Rainbow Spawning applied to flow

Season	all data
Sample size	14480
Minimum	0.000
Maximum	14.765
Mean	10.596
Median	11.580
Standard deviation (denom. = n-1)	3.790

Exceedence statistics for Rainbow Spawning applied to flow

Percent of time AWS is equalled or exceeded	AWS (m^2/m) flow: all data
100	0.000
99	0.000
98	0.000
97	1.348

96	2.708
95	3.517
94	3.892
93	4.230
Etc.	

20.8 Uniform Continuous Under-Threshold Analysis (UCUT)

This analysis requires a daily mean flow series (Time Series>>Open Time Series) and a relationship between flow, AWS and width (Time Series>>Select AWS-Flow relationship). The analysis calculates the percentage of time in bio-period (e.g. spawning season) that AWS is continuously below a specified level (the threshold level) in a bio-period for durations of 1 to the length of bio-period. The threshold level can also be specified as AWS divided by the width at the AWS maxima * 100. For example, if the bio-period was 60 days and the %AWS was below 5% on 5 separate days, 3 separate periods of 2 days, and 1 period of 3 days, the UCUT curve would show 0% cumulative duration for durations greater than 3 days, 5% (3/60*100) cumulative duration for a duration of 3 days, 15% ((3+6) /60*100) cumulative duration for a duration of 2 days, and 23% ((3+6+5)/60*100) cumulative duration for a duration of 1 day.

The bioperiod must be a continuous part of a year (e.g., Dec 15-Jan 15 or May 1 to Sept 1).

Exclusion of high flow AWS

Usually a UCUT analysis will only consider the effect of low flows and ignores the low values of AWS that occur during floods and freshes. The treatment of high flows can be set in the UCUT dialogue by excluding flows above a specified value. The default value is the flow that provides maximum AWS in the AWS/Flow relationship.

When flows are higher than the excluding flow specified in the UCUT dialog, the AWS on that day is not is not considered to below the AWS threshold.

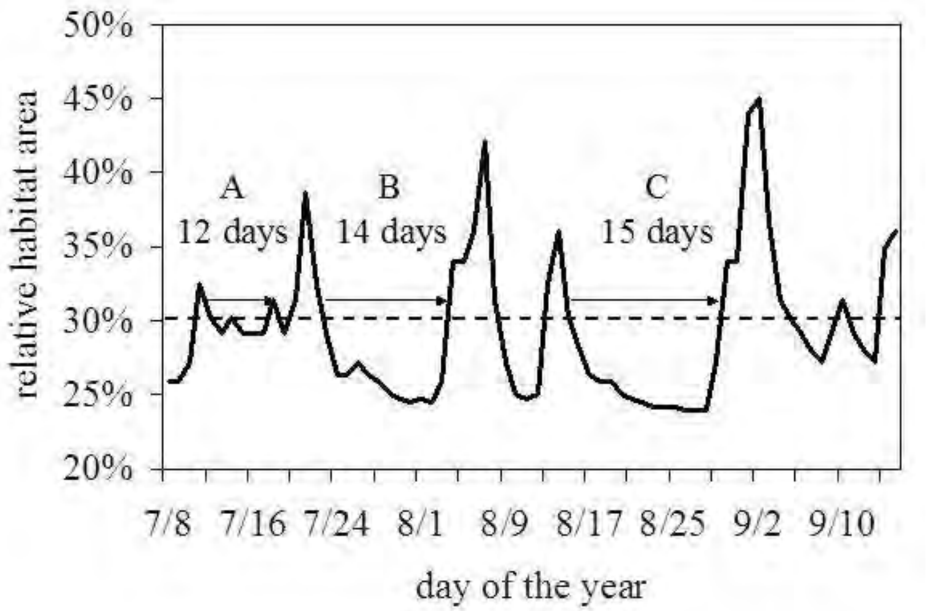
The following description of UCUT was supplied by Piotr Parasiewicz, Rushing Rivers Institute, PO Box 1100, Amherst, MA, USA.

The purpose of this analysis is to investigate flow duration patterns, and to identify conditions that could create pulse and press disturbances as described by Niemi et al. (1990). A pulse stressor is an instantaneous alteration in fish densities, while a press disturbance causes a sustained alteration of species composition. In the habitat analysis, this can be caused either by extreme habitat deficiency regardless of duration or by catastrophically long duration of events with habitat availability critically low. The press disturbance can be caused by frequent occurrence of persistent-duration events with habitat availability critically low. Therefore, the analysis of habitat magnitude, as well as duration and frequency of non-exceedence events serves identifying habitat stressor thresholds (HST).

To identify HST, a habitat time series is developed and the resulting habitat duration curves were analyzed. Next, uniform continuous under-threshold habitat duration curves (UCUT curves) are created (Parasiewicz 2007). As documented by Capra et al. (1995), the curves are good predictors of biological conditions. The curves evaluate the continuous duration and frequency of continuous non-exceedence events for different habitat magnitudes. Rapid changes in frequency pattern are used to distinguish between typical and unusual events and classify them as extreme, rare, critical, and common HST for the low-flow conditions. Rare habitat events happen infrequently or for only a short period of time, categorized below the critical level for habitat circumstances. The critical level defines a more frequent event than rare and has the purpose of specifying management "warning" rather than biological significance. Common habitat levels are the highest defined and should demarcate the beginning of normal circumstances from less common events

Approximations of the threshold within the habitat template are developed from the naturalized hydrograph and habitat rating curves for reference habitat structure. To create our UCUT curves, we first translate the hydrological time series (mean daily flows of the last thirty years) into a habitat time series or "habitograph". Each incremental flow value is converted into a habitat value using a flow-habitat rating curve for a bio-period under the baseline habitat conditions. Thereby, habitat is represented as a function of time.

A habitat event is defined as a continuous period in which the quantity of habitat (relative habitat area) stays under a predefined threshold. In our adaptation, the UCUT curves describe the duration and frequency of events for a given bio-period; therefore, the first step is to extract bio-period data for each year from the habitographs (shown below).



In the second step, the sum of all events of the same duration within each bio-period is computed as a ratio of the total duration of all bio-periods in the record (on the x-axis of the graph). The proportions are plotted as a cumulative frequency (i.e., the proportion of shorter periods is added to the proportions of all longer periods).

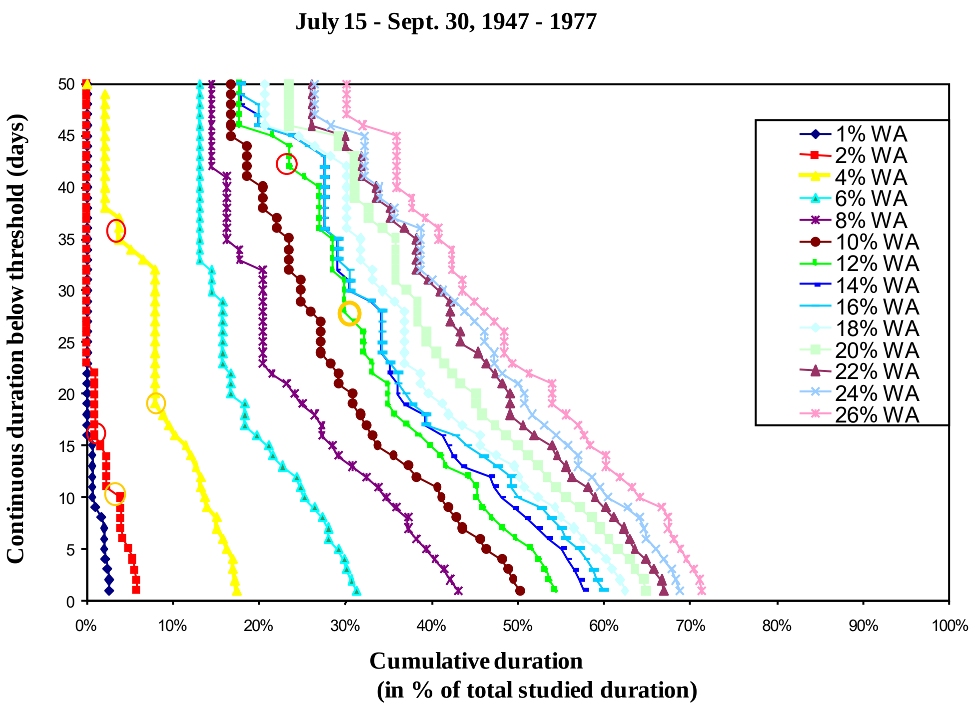
For easier interpretation and calculation, we modified Capra's technique by plotting the cumulative frequency for all continuous durations in days. This results in points for durations with 0% of cumulative increase (e.g., events that did not occur in the time series). For example, if the time series data included events for durations of 14 and 12 days, but not events of 13 days, the CUT curve method would plot only the two points at 14 and 12 days duration. In our method, we also plot the points for a cumulative duration of 13 days (equal in cumulative frequency to the cumulative frequency of 14 days), dropping the line first vertically before joining it with the point for 12 days. To distinguish between the two approaches, we called this adaptation 'uniform continuous under-threshold' (UCUT).

The UCUT curves diagram captures the duration and frequency of events for a given bio-period. The y-axis represents event durations in days. The x-axis represents the cumulative percent duration of events within a bio-period aggregated by increasing duration; the sum length of all events of the same duration within a bio-period is computed as a percentage of the total duration of all years of the bio-period in the record.

This procedure is repeated for the entire set of thresholds with constant increments. The magnitude of the habitat increments between the thresholds is selected on an iterative basis, e.g., changing the increments until a clear pattern can be recognized. We look here for specific regions with a higher or lower concentration of the curves on the plot that would correspond with rare and common events. When many curves are plotted, these two regions are easily identifiable.

The identification of common and less common habitat events is based on the cumulative durations, the shape, and distances between the curves. The procedure has two steps: 1) determination of habitat threshold levels by selecting curves on the graphs, and 2) identification of persistent durations by locating inflection points. Interpretation of these patterns is based on the following observations:

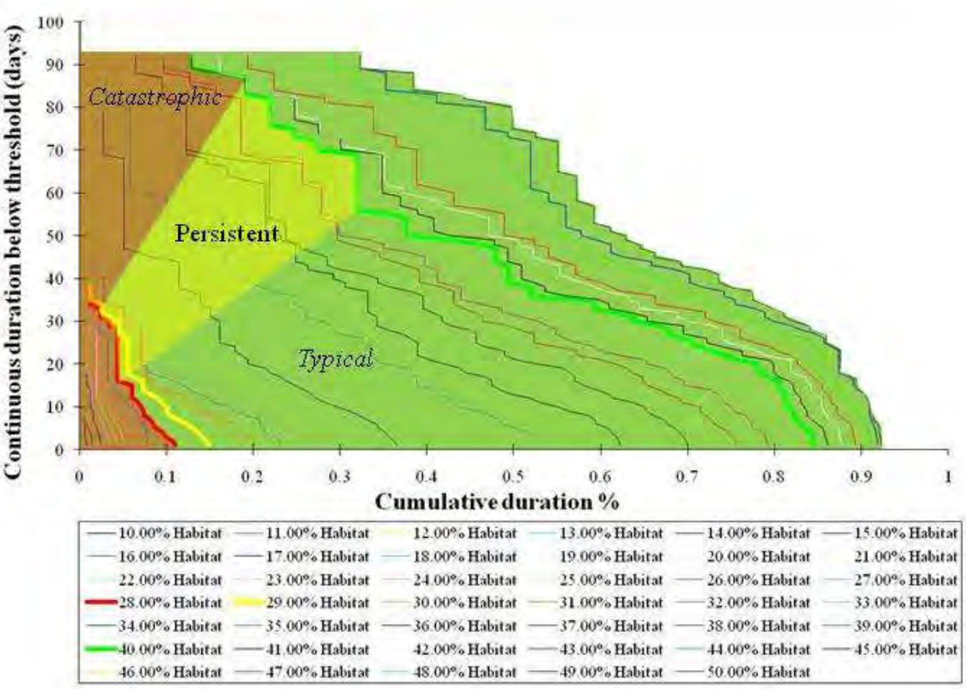
- The curves in the lower left portion of the graph depict rare events (i.e., with low cumulative durations).
- The horizontal distance between curves indicates the change in the frequency of events associated with habitat increase to the next level (i.e., the larger the distance between two curves at the same continuous duration, the larger the change in the frequency of the events).
- Steep curves represent low change in event frequency.
- Inflection points reflect rapid change in frequency of continuous durations.



The curves above indicate selected habitat thresholds in increments of 2 % of wetted area (WA). Based on the density of the curves, three have been selected as significant thresholds for rare (red), critical (yellow), and common (green) events. The circles at the inflection points demarcate transition to persistent (yellow) and catastrophic (red) durations.

Typically, the UCUTs for rare habitats are located in the lower left corner, are steep and are very close to each other. In this range, small increases in habitat level have barely any effect on cumulative duration. As the habitat level increases, this pattern rapidly changes. The highest in this lower-habitat group (before the rapid change of cumulative duration) of curves is defined as a rare habitat level threshold. The rare habitat should be exceeded most of the time. The next highest UCUT line (the first that stands out) is identified as a critical level. The distance between the lines after exceeding the critical level are usually greater than in the previous group but still close to each other. The next outstanding curve demarcating rapid changes in the frequency of events is assumed to mark the stage at which more common habitat levels begin.

Once the threshold levels are identified, the shortest persistent durations indicated by the lowest, convex inflection points on the UCUT curves. Above these points the curves are steep, which show a low frequency of long events. The shortest of the long durations, appearing only on the decadal scale, are defined as catastrophic durations along with their frequency of occurrence.



20.9 Event analysis

An event analysis uses an imported flow file. If an AWS relationship is also selected, the event analysis can be carried out on the AWS values that result from the AWS relationship being applied to the flow variable.

Event analysis allows you to carry out a year by year and season by season analysis of events. To do this you must specify the date/time variable and one or two variables that define the event.

The flow data file is expected to contain daily values. Any missing daily values will be filled by linear interpolation.

If the data file contains only one date variable that variable is selected automatically for this analysis. If there are two or more date variables, those variables are listed and one must be chosen.

The variables that define the event are selected from the drop-down boxes. In the example below, events with flows greater than 3 and less than 21 will be counted each year with the year starting in March and 4 seasons.

Two types of event can be analyzed.

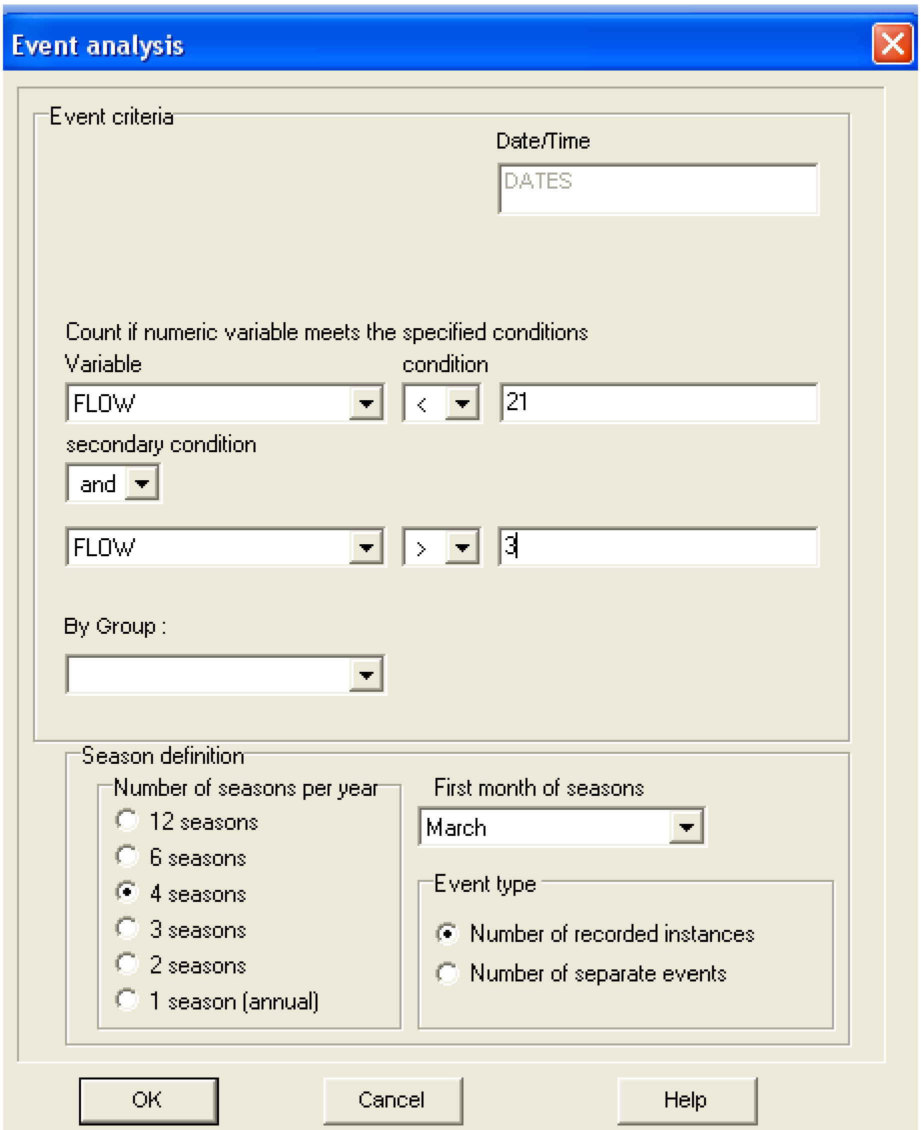
3. Number of recorded instances

The first simply counts the number of times the event is met within each year and season. The meaning of the result will depend on the form of the data. For example, if the data are weekly samples and the analysis reports the number of weekly samples that met the event criteria in each season and year. If the samples were collected daily, the reported result will be the number of days in each season and year that meet the event criteria.

4. Number of separate events

This analysis counts the number of separate (contiguous) events, where the event criteria are met contiguously throughout the event. A separate event begins when the event criteria are triggered and ends when the variable falls outside the event criteria or the season ends. Thus if an event runs contiguously from one season to another or from one year to another, it is reported as two separate events. The season and start month can be adjusted to ensure that the season encompasses the events considered critical.

For example, it is possible to determine the number of flood events, such as required for FRE3, the number of flood events that exceed 3 times the median flow.



The average number of events per year per season is listed, along with the average magnitude of those events.

Duration statistics of contiguous events are reported. These include the maximum, 25% and 75% percentiles, mean, median durations that the criteria are met in any season. The mean annual maximum duration is the mean of the maximum duration of separate (contiguous) events in each year. This is analogous to the mean annual minimum flow.

20.10 Benthic Process Model

This is a time series model of hydraulic conditions (velocity, shear stress, dimensionless shear stress, substrate stability, habitat suitability) and the influence of those parameters on a conceptual model of benthic abundance. The procedure calculates hydraulic parameters at each measurement point of the river model and estimates how these parameters influence the abundance of benthos (e.g., periphyton or benthic invertebrates) at the measurement point. The processes that are considered are population growth through immigration/reproduction, population loss through emigration/mortality, and population movement within the reach as habitat suitability changes.

The benthic growth process comprises two mechanisms, colonisation through drift of invertebrates or plant cells from upstream sources and growth through population increase (e.g., oviposition by insects and physical growth of invertebrates and periphyton). Two growth models are available – logistic and linear. Although few data are available, initial rates of growth after disturbance appear to be higher than predicted by a logistic growth model. For this reason, Hayes et al. used a logistic model with initial (starting) growth rates close to the maximum logistic growth rate. This can be approximated by a simpler linear growth model, as shown below.

A logistic model requires a starting population that is greater than zero and this can be termed resilience. It determines the initial growth rate after disturbance or inundation.

The factor influencing growth is habitat suitability with abundance increasing logistically towards an asymptotic maximum determined by the suitability of the hydraulic conditions at the measurement point. If the measurement point has just been inundated, the initial abundance is assumed to be 1/1000 of the carrying capacity. In the linear model, abundance can increase linearly from zero up to a maximum determined by the hydraulic conditions.

Population change is influenced by three factors. If the population is greater than can be supported by the habitat suitability then the population will decline through emigration. If the measurement point is exposed to the air then 100% mortality is assumed, and if the shear stress is sufficient to move the average substrate size, 100% mortality at the point is assumed, although this effect can be switched off. Seasonality can be accounted for whereby the growth rate is varied sinusoidally through the year.

The input data are a daily flow series, a river model (rhbx file) and a habitat suitability curve. The user is required to enter the summer growth rate per day (r default 0.025), the migration rate as a proportion of the summer growth rate (default 0.5 but would be 0 for non-mobile benthos such as periphyton), and the ratio of winter to summer growth rates (default 0.5). An initial abundance between 0 and 1 is also specified (default 0.4 of the asymptotic maximum).

After substrate disturbance, abundance appears to increase faster than would occur with recolonisation of an inundated or totally clean substrate. This has been described as resilience and may be because of periphyton cells on the substrate surface or invertebrates sheltering within the substrate matrix. This is modelled by using a higher initial growth rate for recolonisation (equivalent to the asymptotic maximum rate) after disturbance than after inundation.

The rating curve is used to calculate water level at each cross-section. The hydraulic rating curve method is recommended as it usually predicts water levels at high flows more accurately than the rating developed by fitting a log-log curve to measured points. The depth at each point is the water level less the bed level and the velocity is calculated by conveyance (i.e., the velocity at each point is proportional to the hydraulic radius to the power of 2/3). Shear stress is calculated from the velocity and friction factor. The friction factor is calculated using the Prandtl von Karman equation assuming *ks* is 3.5 times the d84 substrate size. Dimensionless shear stress is calculated from the median substrate size at each point.

Benthic abundance is calculated on a daily time step.

The logistic model gives the population at any time *t* as;

$P_t = KP_0e^{rt}/(K+P_0(e^{rt}-1))$ where K is the maximum population or carrying capacity (the CSI in this case).

CSI varies with changing flows, so that the time varying rate of change of population is:

$dP/dt = rP(1-P/K_t)$ where r is the intrinsic growth rate and K_t the maximum CSI at time t (carrying capacity)

CSI_t is habitat suitability at time t. The abundance index (0.0001 to 1) at time t-1 is P_{t-1}.

If the population is less than the maximum supported by the suitability of the habitat, growth due to colonisation/migration is $Growth = GrowthRate \times dt \times P_{t-1} \times (1-P_{t-1}/CSI_t)$.

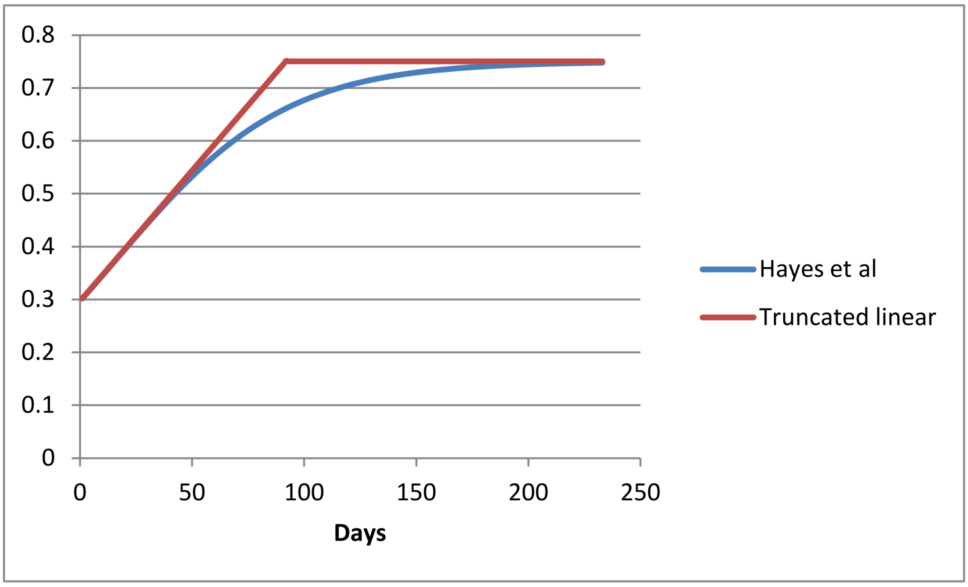
The growth can be approximated by a linear growth model up to maximum CSI_t. r/4 is the maximum growth rate of the logistic model.

$Growth = dt \times r/4 * P_{t-1}$

The benthic population index *BPI* is

$BPI = Min(CSI_t, P_{t-1} + Growth)$

The truncated linear model is similar to the ½ logistic model used by Hayes et al.



If the population is more than the maximum supported by the suitability of the habitat, migration/redistribution of excess population due to reduction in CSI is

$Migration = MigrationRate \times dt \times (P_{t-1} - CSI_t)$, and

$BPI = P_{t-1} - Migration$

21 Sediment

21.1 Hydraulic calculation

The force acting at any point on the streambed is calculated from the bed shear stress by two methods, defined as follows.

1. Slope and hydraulic radius

The bed shear stresses are the forces that resist the effect of gravity on water flow. The sum of the bed shear stresses is proportional to the depth of water and the slope of the river. Thus, the average shear stress over the wetted perimeter can be estimated from the slope and cross-section hydraulic radius.

The slope can be specified as either the (slope between the cross-sections) or the **average slope over the reach**. The default slope is 0.0025 (2.5 m per km).

The slope between cross-sections changes with flow. At low flow, the slope in pools is low and riffles are steeper, but as the flow increases the slope in pools increases and the slope in riffles gradually decreases.

The change in slope with flow can only be modeled if the rating curve at each cross-section is known, either from predicted water surface profiles or stage-discharge curves fitted to calibration gaugings.

In either case, the water level at each cross-section must be related to a common datum and the distance between sections known.

This means that the reach must be surveyed as a representative reach rather than by habitat mapping, where it is not necessary to survey levels to the same datum or to record distances between sections.

Flushing usually occurs at flows higher than the flow that was surveyed. As flows increase, the slope at any cross-section will tend towards the average slope. Thus, an average reach slope should be used if the flushing flows are an order of magnitude higher than the survey flow.

If habitat mapped data are used, flushing flow requirements can be calculated using either the average slope over the reach or friction factor and velocity.

The calculation of bed shear stress from slope and hydraulic radius assumes that the velocity distribution across the section is uniform, i.e., that the velocity at each point is proportional to the depth. At high flows, this will be true in many cases because small obstructions that effect the velocity distribution will be drowned.

If use slope and hydraulic radius is checked then bed shear stress is calculated from the slope and hydraulic radius

bed shear stress = wRS

dimensionless bed shear stress = RS/(sg-1)/median substrate size

where *w* is the specific weight of water (density x g), *R* is the hydraulic radius, *S* the slope, *substrate size* the median surface sediment size (d50), and *sg* the specific density of the substrate.

The calculation of bed shear stress from slope and hydraulic radius assumes that the velocity distribution across the section is uniform, i.e., that the velocity at each point is proportional to the depth. At high flows, this will be true in many cases because small obstructions that effect the velocity distribution will be drowned.

2 Velocity, friction factor and substrate size

Alternatively, the velocity method can be used where the slope is calculated indirectly from velocity and substrate measurements.

If Friction factor and velocity is checked then bed shear stress is calculated from friction factor and velocities at each point calculated with or without VDFs depending and whether the Use VDFs option is checked. The d84 sediment size is used to calculate the friction factor and the median sediment size is used to calculate the dimensionless shear stress.

A more theoretically based equation than Manning's equation was developed by Darcy and Weisbach for determining head losses in pipes. When adapted for open channel flow it can be written as:

$v^2 = 8g \times R \times S / f$ and $R \times S = f \times v^2 / (8g)$

where f is the friction factor and v the velocity.

Shear velocity $v^* = sqrt(g\ RS) = sqrt(f\ v^2 / 8)$

The Prandtl von Karman equation can be used to calculate *f* from substrate size. If substrate data are not available, the specified median armour size is used.

$Sqrt(8/f) = 5.75 \times log_{10}(12.2 \times R / k_s)$

Where k_s = constant times particle size. A variety of constants have been fitted, and the average seems to be about $k_s = 3.5\ d_{84}$ (Hey 1979).

$Sqrt(8/f) = 5.75 \times log_{10}(12.2 \times R / (3.5\ d_{84}))$

$f = 8 / ((5.75 \times log_{10}(12.2 \times R / (3.5\ d_{84})))^2)$

Shear velocity $= sqrt(v^2 / 8) \times sqrt(f)$

Shear velocity $= sqrt(v^2 / 8) \times sqrt(8 / ((5.75 \times log_{10}(12.2 \times R / (3.5\ d_{84})))^2))$

Shear velocity $= \mathbf{sqrt(v^2 / 8) \times 1/(2.03 \times log_{10}(12.2 \times R / (3.5\ d_{84})))}$

The above equation breaks down when the depth is shallow compared to the substrate size.

To prevent unreasonably high values of shear velocity, the above equation is applied when the hydraulic radius is greater than 3.5*d_{84}. When the hydraulic radius is less than 3.5 times the substrate size (d_{84}), the shear velocity is calculated as:

Shear velocity = sqrt(V^2 */8) x 1/(2.03 x* log_{10}*(12.2)))*

And dimensionless shear stress is:

Dimensionless Shear Stress = sqr(Shear velocity)/g/(sg-1)/median substrate size

When shear stress is calculated from velocities, the velocity distribution factors can either be set to 1 to give a uniform distribution (as is likely at high flows) or applied (use VDFs checked) to reproduce the measured velocity distribution.

The former option (not to use VDFs) is recommended for the calculation of deposition and flushing at high flows.

The default **slope** is the average slope over the reach calculated from the distance between the first and last cross-section and the difference in water levels between these two cross-sections. If the reach is habitat mapped without accurate distances and water levels referenced to a common datum, the value of slope should be ignored and a correct value (e.g., determined from topographic maps) entered.

21.2 Substrate size and flushing flows

For instream habitat analyses the percentage of a substrate type is the percentage of the bed area covered by that substrate size category. This method is used because substrate suitability (i.e., based on substrate size category) is one of the factors that are multiplied by area to determine area weighted suitability (AWS). The percentage substrate type at a point is also applicability to sediment analysis and similar to the Wolman method.

Kellerhals & Bray (1971) discuss various methods for sampling river sediments and in their terminology instream habitat substrate is “grid by number”, which they show is analogous to studies using uniformly sized sediments. The substrate composition in most sediment transport studies is sampled either by the Wolman method (“grid by number”) or “area by weight”. The former being a classification of the percentage of the number of particles sampled (pebble count) and the latter a percentage of the total weight of particles sampled.

The median substrate size given by these two methods differs. The median size determined by “grid by number” (i.e. as for an instream habitat survey) will give a smaller median size than “area by weight”.

The calculation of the amount of disturbance caused by a flow is based on bed shear stress and substrate size. Shield's showed that particles were likely to move when the dimensionless bed shear stress equaled 0.056. Milhous used data from a small gravel bed stream to show that surface sediments were flushed when the dimensionless bed shear stress exceeded 0.021 and that the armour layer was disturbed when the stress exceeded 0.035. These values are used to calculate the area of the streambed that is flushed.

The effect of bed shear stress at point depends on the substrate size. Obviously, large substrate requires higher stresses for movement than small substrate.

If **median substrate size (d50) mm** is checked, the median bed sediment size is used to calculate flushing flow effectiveness at each point.

If not checked, the d50 substrate size at each point is calculated from the substrate composition at each measurement point.

The median substrate size is interpolated from the percentage composition of each size category.

For example, if a point measurement comprises 20% fine gravel, 40% gravel (8-64mm) and 40% cobble (64-256mm) then it is assumed that half (10%) of the fine gravel will be less than the median fine gravel size (default 5 mm), half (20%) of the gravel will be less than the median gravel size (default 36 mm) and half (20%) of the cobble will be less than the median cobble size (160 mm), Thus, 10% of the substrate is >5 mm, 40%of the substrate is >36mm and 80% > 160 mm.

Median size = 36 + 10/40*(160-36) = 67 mm.

The size of suspended and bedload sediments moved by a flow are calculated from formulae presented by Milhous (1998).

These are:

Max. suspended sediment size = Slope x hydraulic radius/((Specific gravity-1) x 0.28)

Median bedload size = Median substrate size x (Slope x Hydraulic radius /((Specific gravity - 1) x 0.046 x median substrate size))^2.85

Maximum bedload size = Median substrate size x (Slope x Hydraulic radius /((Specific gravity - 1) x 0.018 x median substrate size))^2.85

The bedload equations above are used when the median bed load size is less than the median substrate size. When the median bed load size exceeds the median substrate size, the hiding effect of the substrate no longer applies and the equations become:

Median bedload size = Slope x Hydraulic radius /((Specific gravity - 1) x 0.046)

Maximum bedload size = Slope x Hydraulic radius /((Specific gravity - 1) x 0.018)

Where slope is not used in the calculation of bed shear stress, the slope/hydraulic radius product is the bed shear stress calculated by the alternative method (see 2 above) divided by the specific weight of water.

Milhous (1998) used “area by weight” to calculate median particle sizes when he defined dimensionless shear stresses for flushing and channel maintenance flows (R Milhous, pers. comm.).

Kellerhals & Bray (1971) describe how to convert field data between the sampling methods. The median substrate size used by Milhous (1968) was probably about 44 mm (area by weight) compared to a median size of about 22 mm by Wolman sampling.

Milhous (1968) defined his formulae based on the average channel shear stress, whereas in SEFA the formulae are applied to each measurement point and then summed over the channel to give the percentage of the bed over which substrate movement occurs.

An analysis can also be performed using Gessler's (1970) criterion for the initiation of bed movement. This method incorporates a hiding factor, under the assumption that large substrates "hide" small substrate from the effects of the current. There is good agreement between the Gessler (1970) and Milhous (1998) methods, with Gessler's method having the advantage that it predicts the probability of movement for all sediment sizes. The hiding factor is incorporated into the calculations in the term:

$(d_i/d50)^h$

where d_i is substrate size and h is the hiding factor.

The hiding factor increases the effective shear stress on small particles to allow for the hiding effect of the larger particles. Values of the exponent h could vary from 0.113 (Andrews 1984) and 0.33 (Duncan & Biggs 1998). A value of 0.113 is used in SEFA.

These differences do not appear to alter the efficacy of flushing flow calculations, as field testing indicates that the flushing flow recommendations based on SEFA analyses achieve satisfactory results. This is because with mixed gravel sediment there is no single value of shear stress at which sediment begins to move (e.g., a critical shear stress), as shown by the experiments of Helland-Hansen et al. (1974), who concluded "The data presented in this paper indicate that sediment transport is possible at very low values of the Shields parameter. Some methods of estimating the bed material movement in a stream assume that below some critical shear stress the sediment transport rate is zero. Based on work presented herein, it is clear that there is some probability of sediment transport at all levels of bed shear stress and, in the words of Paintal (1965), "this probability is never zero except in still water."

References

Gessler, J. (1970). Self-stabilizing tendencies of alluvial channels. Journal of the Waterways and Harbors Division. Proceedings of American Society of Civil Engineers 96: 235-249.

Helland-Hansen, E.; Milhous, R.T.; Klingeman, P.C (1974). Sediment transport at low shields-parameter values. Journal of the Hydraulics Division, ASCE. Vol. 100 no. HY1. Pp 259-265.

Hey, R.D. (1979). Flow resistance in gravel-bed rivers. Journal of Hydraulics Division 105(HY4): 365–379.

Kellerhals, R.; Bray, D.I. (1971). Sampling Procedures for Course Fluvial Sediments. Journal of the Hydraulics Division. ASCE. Vol.97, no. HY8, August,1971. Pp 1165-1180.

Milhous, R.T. (1998). Modelling instream flow needs: the link between sediment and aquatic habitat. Regulated Rivers: Research and Management 14: 79-94.

Paintal, A. S. (1965). "The Probabilistic Characteristics of Bed Load Transport in Alluvial Channels," thesis presented to the University of Minnesota, at Minneapolis, Minn., in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Baseflow

The base flow is the "normal" flow for a particular time of year.

As flows increase, a river widens with shallow depths and low velocities along the margins and velocities are rarely high enough to cause 100% flushing over the entire stream bed.

However, usually flushing flows are intended to remove fine sediments from the "baseflow" channel.

If **baseflow** is checked and the base flow entered, substrate stability is evaluated only for the base flow channel.

21.3 Sediment deposition

Sediment deposition occurs in areas where the water velocity is low enough to allow sediment to settle. The area of potential sediment deposition is calculated for two sizes of sediment sand (2 mm) and silt (0.064 mm) over the specified range of flows.

The force acting at any point on the streambed is calculated from the bed shear stress, defined as:

bed shear stress = wRS

dimensionless bed shear stress = RS/(sg-1)/median substrate size

where *w* is the specific weight of water (density x g), *R* is the hydraulic radius, S the slope, and *sg* the specific density of the substrate.

The slope at a cross-section changes with flow. At low flow, the slope in pools is low and riffles are steeper, but as the flow increases the slope in pools increases and the slope in riffles gradually decreases.

The change in slope with flow can only be modeled if the rating curve at each cross-section is known, either from predicted water surface profiles or stage-discharge curves fitted to calibration gaugings.

In either case, the water level at each cross-section must be related to a common datum and the distance between sections known.

This means that the reach must be surveyed as a representative reach rather than by habitat mapping, where it is not necessary to survey levels to the same datum or to record distances between sections.

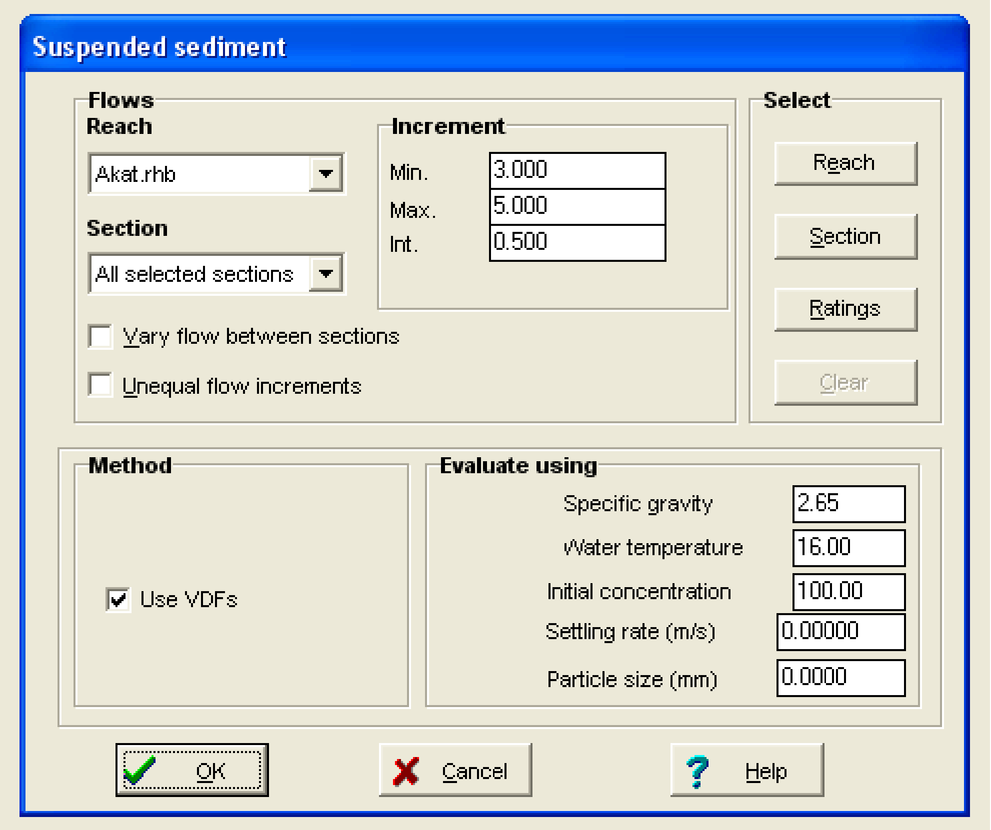
The slope calculation option is available only with reach data, otherwise *RS* is calculated at each point using friction factor and velocity, as described above.

Shield's showed that particles were likely to move when the dimensionless bed shear stress was greater than 0.056. The area of potential deposition is the area where the dimensionless shear stress is less than 0.056.

21.4 Suspended sediment

The reduction in suspended sediment concentration due to deposition/trapping of sediment in dead zones is calculated using the method described by Einstein (1968). This process results in the water clarity improving with distance downstream. The rate at which clarity (suspended sediment concentration) improves depends on the particle size and hydraulic characteristics of the river.

This theory assumes that the bed is "sticky" and any particle reaching the bed is trapped in the gravel matrix or periphyton layer. If the bed is smooth and sediment non-cohesive, some or all re-suspension is likely and field calibration of any model is advisable.



The initial concentration of the suspended sediment is specified. This can be an actual concentration of 100 to give the reduction in percentage concentration.

The calculation assumes that there is no additional suspended sediment from tributaries or bank and bed erosion.

The weight of sediment (uniform concentration c, fall velocity Vs) deposited in a small segment of a uniform channel cross-section area A, width W, depth Y, length dx and mean velocity V is given by Einstein (1968) as:

c Vs Y W dt where *dt* is the time in transit = *dx/V*.

The weight deposited is therefore *c Vs A dx/V*.

An element of a non-uniform channel has an area dA, length dx, depth y, width dw, velocity v so that the time that a particle is in transit is dx/v and the amount of sediment reaching the stream bed is:

c y Vs t dw = c y Vs dx/v dw = c Vs dx/v dA

and the rate over the whole stream bed is $\int c v_s \frac{dx}{v} dA$.

Let α times the weight deposited in a channel of mean depth and velocity equal the weight deposited in a non-uniform channel

$$\int c v_s \frac{dx}{v} dA = \alpha c v_s \frac{dx}{V} A$$,

As *c, Vs* and *dx* are constant across a cross-section, the coefficient is $\alpha = \frac{\int 1/v \, dA}{A/V}$ and is always greater than 1 for a non-uniform channel.

The characteristics of the suspended sediment are described by either the settling rate (velocity m/s) or particle size in mm.

The settling rate (Vs), particle size (d), water temperature (T) and specific gravity (SG) are inter-related.

*Vs = Sqr(d)/Viscosity(T)*9.81/18*(SG-1)*

where Viscosity(T) is the viscosity of water at temperature T.

Viscosity(T) = 10E-6(1.5459-(T-4.44444)*0.56206/16.6666667)*

The suspended sediment concentration (C) is calculated at distance X metres using average reach parameters water depth (D), velocity and alpha as:

*C = exp(logC- α /D * X/velocity * Vs)*

The water depth (D) is the cross-section average depth (Area/width) and velocity is the cross-section average velocity (Flow/Area).

LogC is the natural logarithm of the initial suspended sediment concentration.

Alpha (α) is an integrated cross-section parameter similar to the energy coefficient and is a measure of the amount of dead zones in the reach. Its value is influenced by the transverse velocity distribution, and using VDFs will result in a non-uniform velocity distribution and hence more suspended sediment deposition.

It is possible to use measurements of suspended sediment (or any fine particle) at points along a river to calibrate the model by adjusting particle size to match observations.

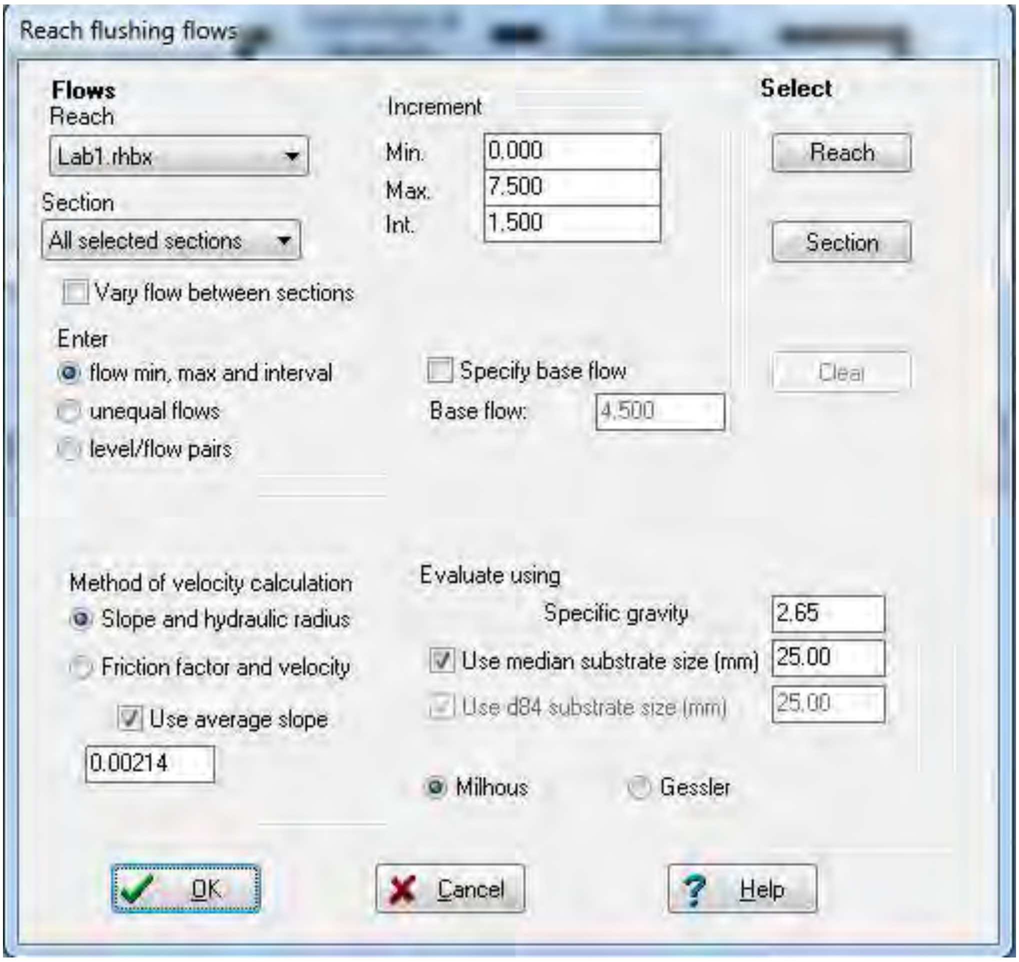
21.5 Flushing flows

Flushing flows are flows that remove the fine sediments and periphyton accumulations from stream substrates. Flushing flows are necessary in most streams to remove accumulated fine sediments and to restore interstitial space in gravel substrates.

Slope in the dialogue below is the average slope over the reach calculated from the distance between the first and last cross-section and the difference in water levels between these two cross-sections. If the reach is habitat mapped without accurate distances and water levels referenced to a common datum, the value of slope should be ignored and a correct value (e.g., determined from topographic maps) entered.

Surface flushing flows remove the fine sediments from the surface layer, leaving the armour layer largely intact. Periphyton will also be removed by the abrasive action of fine sediments moving over the surface.

Deep flushing flows disturb the armour layer, removing the sediments that have deposited within the gravel matrix.



Flushing is calculated from the shear stress (SS), R hydraulic radius, S slope, g gravity,

SS = Sqrt(gRS)

If you enter the slope, all the program does is calculate the shear stress at each point from the hydraulic radius at that point. This assumes the same slope at all cross-sections, which is likely at high flows. It then calculates the dimensionless SS by applying the median substrate size, using either the median that you supply or the median calculated from the substrate composition at the point (this is set in the dialogue).

If you elect to calculate using friction factor and velocity, bed shear stresses are calculated from the friction factor and velocity using the Darcy-Weisbach and Prandtl von Karman equation using R at the point, the substrate size (d m) at the point, and the predicted velocity V at a point.

22 Water temperature

Water temperature modeling is included to help aquatic biologists and engineers predict the consequences of stream manipulation, either flow or shade, on water temperatures. Water temperatures may affect aquatic systems in many ways, ranging from acute lethal effects, to modification of behavioral cues, to chronic stresses, to reductions in overall water quality. Manipulations may include reservoir discharge and release temperatures, irrigation diversion, riparian shading, channel alteration, or thermal loading. The model has been used in the U.S. to help formulate instream flow recommendations, assess the effects of altered stream flow regimes, assess the effects of habitat improvement projects, and assist in negotiating releases from existing storage projects.

The model is a mechanistic, one-dimensional heat transport model that predicts the daily mean and maximum water temperatures as a function of stream distance and environmental heat flux. Net heat flux is calculated as the sum of heat to or from long-wave atmospheric radiation, direct short-wave solar radiation, convection, conduction, evaporation, streamside vegetation (shading), streambed fluid friction, and the water's back radiation. The heat flux model includes the incorporation of groundwater influx. The Lagrangian heat transport model tracks heat and water fluxes downstream whereas the Theurer model uses numerical solutions to the heat flux and transport equations.

The water temperature models assume that all input data, including meteorological and hydrological variables, can be represented by 24-hour averages or sinusoidal variation about the average.

Water temperatures are modeled downstream of a section of river.

The initial water temperature at the head of the reach must either be specified or calculated from the stream characteristics upstream of the reach.

Water flowing downstream will the increase or decrease in temperature until the incoming radiation equals the heat lost from the river through radiation and evaporation. The temperature at which incoming energy equals the outgoing energy and there is no further increase in water temperature is known as the equilibrium temperature.

The units of temperature are degrees Centigrade and the units of radiation are J/sec/m^2 or W/m^2.

The change in water temperature is calculated as the water flows downstream using the initial water temperature at the beginning of the reach.

The magnitude of the change will depend on meteorological conditions such as radiation and air temperature and the flow.

Method

This program carries out a numerical (Lagrangian) solution of the differential heat balance equations as described in:

Rutherford, J.C.; Blackett, S.; Blackett, C.; Saito, L.; Davies-Colley, R.J. 1997. Predicting the effects of shade on water temperature in small streams. New Zealand Journal of Marine and Freshwater Research 31: 707-721.

The equations are similar to those described by Fred D. Theurer in:

Theurer et al. 1984. Instream water temperature model. United States Fish & Wildlife Service. Instream flow information paper 16.

Theurer's method of calculating daily mean water temperatures and daily maximum temperatures can also be shown (by checking option in Graph Options).

22.1 Limitations

- The characteristics of the selected reach or reaches represent the characteristics of a longer section of river and do not change with lateral inflow.

- The model does not handle rapidly fluctuating flows.

- Turbulence is assumed to thoroughly mix the stream vertically and transversely (i.e., no micro thermal distributions).

Three independent sets of conditions must be specified:

- Initial water temperature

- Hydraulic conditions (flow)

- Meteorological conditions

22.1.1 Initial water temperature

The initial water temperature is the temperature of the water flowing into the upstream end of the reach. Its units are degrees Centigrade.

By default, this is the equilibrium temperature calculated assuming an infinitely long upstream channel with the same characteristics as the reach, including flow and shade. If the default assumption is true, there will be little change in temperature with flow and distance downstream.

Note that differences in the amount of shade between upstream and downstream reaches and differences in flow (e.g., as created by abstraction of water), will probably invalidate the default assumption of equilibrium.

The initial water temperature can be changed by specifying a water temperature in the advanced options that are available after modeling with default options or by altering the characteristics of the upstream channel (also in the advanced options).

22.1.2 Flow

The flow or range of flows to be modeled effects the velocity and depth of water. The rate at which water flows and the area river exposed to radiation, influences the rate of increase of water temperature. Zero flows cannot be modeled.

22.1.3 Lateral and point inflow

The calculation assumes that lateral inflow (or outflow if negative) is either uniformly apportioned through the length of the segment or flows in at a point. This option is not available in the Theurer model. Point inflows enter at the distance down the reach that is specified.

The temperature of the uniformly distributed lateral inflow generally should be the same as groundwater temperature. In turn, groundwater temperature may be approximated by the mean monthly air temperature. Exceptions may arise in areas of geothermal activity.

22.1.4 Daily mean air and ground temperature

All temperatures are in degrees Centigrade. Daily means are usually the average of the daily maximum and daily minimum temperatures.

Ground temperatures are measured at 1.0 m below ground level, but this can be altered in the advanced options.

If ground temperatures are not available use mean monthly air temperatures.

Air temperatures should be measured for accurate results; however, this and the other meteorological parameters may be obtained from the National Institute of Water and Atmospheric Research for a weather station near your site. ' Use the adiabatic lapse rate to correct for elevation differences:

Ta = To + Ct * (Z - Zo)

where Ta = air temperature at elevation E (C)

To = air temperature at elevation Eo (C)

Z = mean elevation of stream (m)

Zo = elevation of met. station (m)

Ct = moist-air adiabatic lapse rate (-0.00656 deg C/m)

NOTE: Air temperature will usually be the single most important factor in determining water temperature.

22.1.5 Wind velocity

The average daily wind velocity over the water surface in m/s. The wind velocity at meteorological stations is often higher than that at water surface level. Adjustment of wind velocity (and shade) can be used to calibrate a water temperature model to known downstream water temperatures.

22.1.6 Humidity

The relative humidity is specified as a decimal value.

Correct for elevation differences by:

Rh = Ro * (1.0640 ^ (To-Ta)) * ((Ta+273.16)/(To+273.16))

where

Rh = relative humidity for temperature Ta (decimal)

Ro = relative humidity at station (decimal)

Ta = air temperature at stream (deg C)

To = air temperature at met. station (deg C)

^ = exponentiation

0 <= Rh <= 1.0

22.1.7 Elevation

The elevation in metres above sea level at the start of the stream reach to be modeled. The maximum length of any stream reach is the elevation divided by the gradient, i.e. the point at which sea level is reached.

22.1.8 Slope

The average friction slope (usually the bed slope) of the stream reach in metres/metre.

22.1.9 Radiation

The average daily radiation is one of the most important factors affecting water temperature. Radiation is highest in mid-summer and lowest in winter. It is entered in units of $J/m^2/sec$ (W/m^2) with a pyrometer. The conversion from $MJ/m^2/d$ is to multiply by 1000000 and divide by 86400.

22.1.10 Shade

This is the proportion of the water surface that is shaded. Every stream or river is shaded by the banks and surrounding hills and vegetation. The proportion or shade angle is estimated as the proportion of sky visible in a 180 deg arc of the sun. Shade represents the proportion of the incoming solar radiation that does not reach the water. The amount of shade can be determined either by a trial and error calibration procedure to a known downstream water temperature or by measurement.

More complex shading can be specified in the advanced options, where the average topographic angle (shade from topography), average canopy angle (shade from riparian vegetation), and the fraction of radiation penetrating the vegetation canopy can be specified separately.

Shade fraction is calculated as topographic shade plus canopy shade.

Topographic shade = 1 – $(\cos(\text{topographic angle}))^2$

Canopy shade = (1 - Fraction penetrating Canopy) * $((\cos(\text{topographic angle}))^2 - (\cos(\text{canopy angle}))^2)$

The canopy angle must always be equal to (no vegetation) or greater than the topographic angle.

22.1.11 Sunshine hours (decimal)

This parameter is an indirect measure of cloud cover. It is measured with a pyrometer.

The sunshine hours can be calculated from cloud cover (decimal) as:

Fraction sun = 1 - Cloud^(5/3)

Sunshine hours = Fraction sun * daylight hours

22.1.12 Day number and Latitude

The day number and latitude are used to calculate the day length and sun angle (solar elevation) at different times of day and hence the times at which the stream is shaded by topography or riparian vegetation.

22.2 Calibration of water temperature model

Calibrate/Run reach temperature series enables the import of a time series of climate, flow, and water temperature data. Shade, wind, and bed conductivity can then be adjusted to calibrate the model for both the Lagrangian and Theurer models. Maximum temperature predictions can also be compared to measured maximum temperatures, and this may show a difference in the ability of the two models to predict daily maximum temperature.

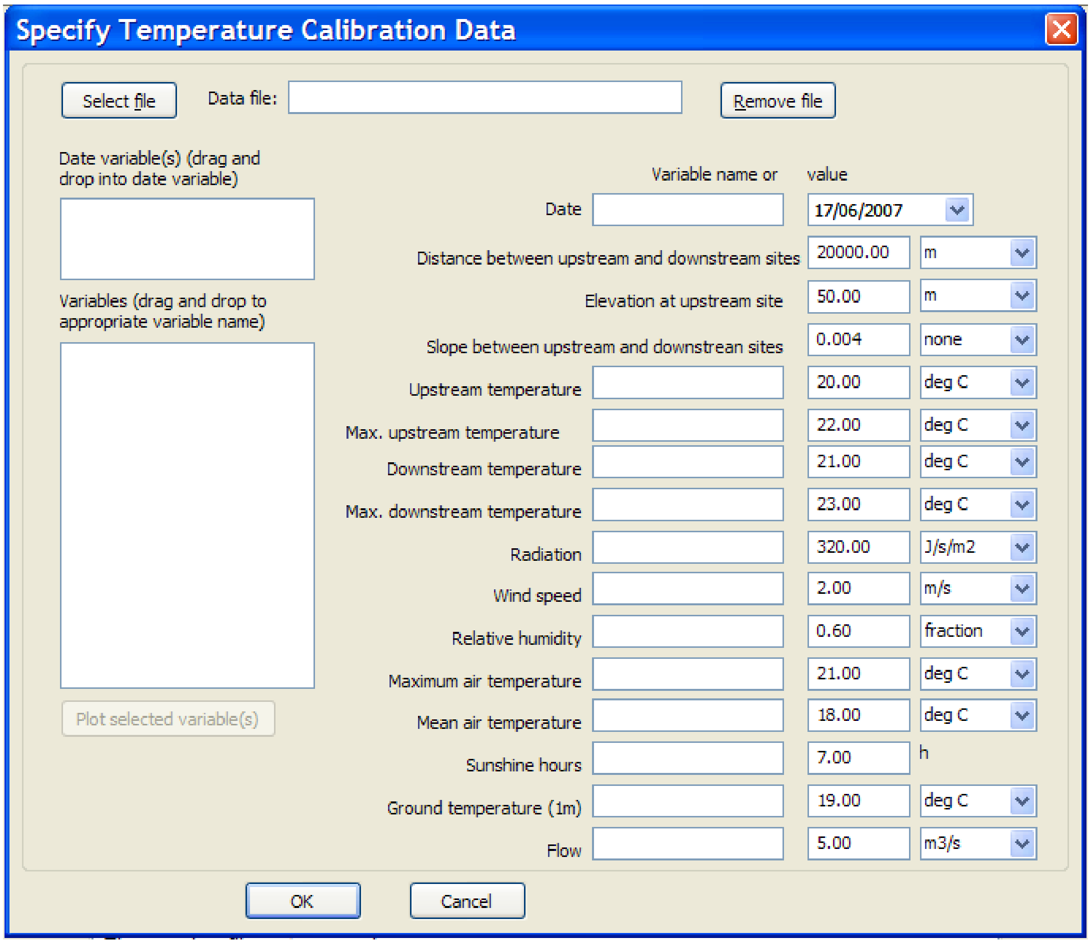
The time series model can be run with different flows series by including the flow series in the dataset that is imported. First fit the model with the measured flows and then rerun the model (with fitted parameters) for the modified flows.

Modeling the effects of flow on water temperature can also be carried out using the Temperature/Reach model menu. Flows and climate data are entered and the variation of maximum, minimum and daily mean water temperature with distance downstream is shown as a graph.

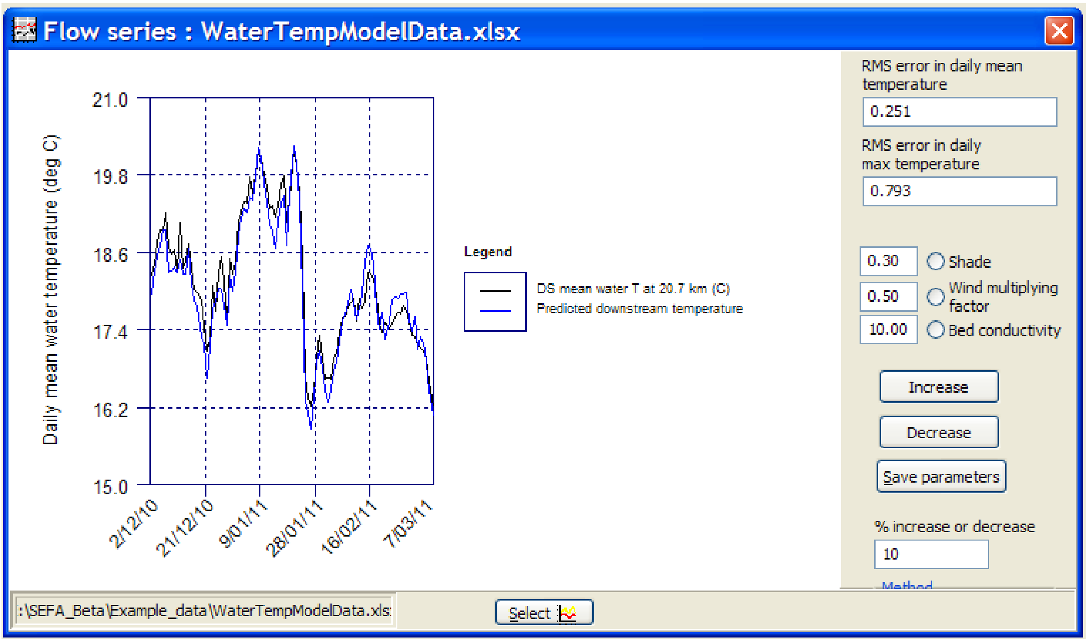
Once a hydraulic reach model is opened, a water temperature model can be calibrated using the menu item Calibrate/Run reach temperature series and a file of measured flow, meteorological and water temperature data, although this is not necessary in order to get a rough idea of the temperature changes that will be caused by a change in flow.

Calibration data include field measurements of upstream and downstream daily mean water temperatures, flow, and meteorological conditions. These can be used to calibrate the shade factor, a factor to multiply measured wind velocity, and bed conductivity so that the model predicts the correct downstream water temperature. Errors in prediction are given for both model formulations.

The calibration procedure involves importing a file (*.xls*, *.csv etc.) with the calibration data and then dragging and dropping the various date, meteorological, water temperature, and flow variables into the appropriate model boxes. If no data are available for any of the items, constant values can be specified. File units can be either metric, US or a mixture of both.



Once imported, the procedure displays a graph of measured and predicted water temperatures at the downstream site. Shade, wind multiplication, and bed conductivity can then be adjusted with a click of a button to develop a model with the best possible temperature prediction. This can be done with both the Theurer solution and the Lagrangian solutions.



22.2.1 Modeling temperature variation with flow

The reach water temperature model predicts how water temperatures vary with distance down a reach. Tributary inflows can be allowed for by entering the location and characteristics of the tributary. Initial conditions at the upstream end of the reach can either be specified temperatures or equilibrium conditions.

Multiple reaches and sections

A number of reaches (reach button) or a selection of cross-sections (section button) may be specified and water temperatures will be calculated for a section of river with hydraulic characteristics that are an average of all reaches

22.2.2 Time series water temperature model

The water temperature calibration model can be used to model a water temperature time series for different flow scenarios. For example, if calibration data are imported for measured flows, the model can then be calibrated. If the measured flows are replaced by a different flow scenario, the model predications will show the water temperatures that result from the new flow scenario,

The procedure is described in the example_data files:

1. Open the river data file River_data_for_Water temperature data.rhbx

2. Set time zone and location. The example data were collected in the southern hemisphere, so the location should be set to:

> 12 hours from GMT
> Latitude (deg min) 38 5.28' South
> Longitude (deg min) 176 42.0' East

3. Calibrate/run reach temperature series

4.Select file (with temperature series, flow data and meteorological data). This is the file WaterTempModelData.xlsx.

5. Drag Date, upstream water temperatures (mean and max), downstream water temperatures (mean and max) etc. to the appropriate position to the left.

6. Select the appropriate units for each variable (with these data, RH, Radiation and wind speed and possibly flow should be changed)

7. Enter the distance between upstream and downstream sites (20.7 km or 30.4 km depending on the pair of downstream temperatures that were selected)

8.Enter elevation and slope (say 50 m and 0.004)

9. Press OK then vary shade, wind factor and bed conductivity to get the best fit.

10. Select the Lagrangian model test whether you can get a better model

of daily mean and maximum temperatures than with the Theurer model.

11. Save parameters to predict downstream water temperatures for subsequent runs with different flow, upstream temperatures or meteorological data

12. The example file WaterTempModelRunData.xlsx has the data that could be used to predict a 20% reduction in flow with the same conditions that were used for calibrating the model.

23 Dissolved oxygen modeling

23.1 Introduction

Three important parameters, as well as stream geometry and water temperature data, are required to calculate flow effects on dissolved oxygen concentration. These are:

daily community respiration rate (the average rate of oxygen consumption by aquatic plants and micro-organisms),

production/respiration ratio (ratio of the daily rates of photosynthetic production of oxygen to daily oxygen respiration by plants and micro-organisms), and

re-aeration coefficient (the coefficient that describes the rate at which oxygen is exchanged between the atmosphere and the stream).

Diurnal DO is affected by three fundamental processes: re-aeration, plant and bacterial respiration, and photosynthesis, as described by the following equation for the rate of change in dissolved oxygen, dC/dt:

$$dC/dt = k(C_s - C) + P - R$$

where C is the dissolved oxygen concentration at time t, C_s is the saturation value for dissolved oxygen (and depends on water temperature), k is the re-aeration coefficient, and P and R are the instantaneous rates of photosynthetic production and respiration by plant and micro-organisms at time t, respectively. Dissolved oxygen is expressed in units of grams of oxygen per cubic metre of water ($g(O_2)/m^3$) or the equivalent milligrams of oxygen per litre of water ($mg(O_2)/L$).

23.2 Calibration of dissolved oxygen parameters

Field measurements are used to calibrate reach and network DO models.

For the reach model, the recorder should be located at the downstream end of a uniform reach. For the network model, DO recorders are located at the upstream end of the reach, in major tributary inflows, and the downstream end of the reach to provide calibration data.

Diurnal variation of dissolved oxygen concentration and water temperature collected using a DataSonde, or similar recorder, during periods of stable weather can be used to calculate re-aeration, respiration and production rates. The period used for analysis should exclude measurements made at the start and end of the DataSonde deployment because they are often affected by odd electrode responses that occur during the transfer to the stream site. Most importantly, it is important to establish a pattern in the diurnal variations and choose the parameter values that best represent the whole data set.

If flow measurements are made during the DataSonde deployment, they can be used to examine how oxygen parameters vary with flow.

23.3 Description of terms

Temperature adjustment and Q10

The instantaneous re-aeration coefficient (k_2) is corrected to a standardized value at 20°C from the daily mean water temperature *Tav* using the temperature-correction factor of Elmore & West (1961)

$k_2^{(20)} = k_2^{(Tav)} \times 1.0241^{20-Tav}$ (4)

where $k_2^{(20)}$ is the value of k_2 at 20°C and $k_2^{(Tav)}$ is the value of k_2 at *Tav*.

The respiration rate [R, g (O_2) m^{-3} d^{-1}] at temperature *Tav* is related to its standardized value at 20°C (i.e., $R^{(20)}$) via a "Q_{10}" factor, i.e.,

$$R = R^{(20)}\left(e^{\frac{\lambda n(Q_{10})}{10}}\right)^{Tav-20}$$ ....(5)

so that if Q_{10} = 2 and T = 30°C, then $R = 2R^{(20)}$, as required.

Q_{10} should lie between 1 and 2.

Photosynthetic production rate [P, g (O_2) m^{-3} d^{-1}] is adjusted in the same manner, thus retaining a constant ratio of average production to respiration (P over R).

Reference flow

The reference flow (Q_{ref}) is the flow (m^3/s) to which the estimated oxygen parameters apply and this will usually be the flow at which calibration measurements were carried out. The reference flow is only used when modeling the variation in dissolved oxygen concentration with flow.

The reference flow and the corresponding value of depth is used to adjust respiration rates and photosynthetic production.

When the flow changes, the biomass of macrophytes per square metre of stream bed is assumed to remain constant and the flow change alters the water depth and thus dilutes or concentrates the oxygen produced or taken up by the plants. The equation for the change in DO ΔDO over a time interval t is:

$$\Delta DO = [k(C_{sat} - C) + P - R]$$

Where t is in days, k is re-aeration in units of /d, and P & R are production and respiration in g/m^3/d.

Consider a square metre compartment of the river as if you were travelling downstream at stream velocity. The water velocity relative to the observer is zero and the bed of the stream is producing or taking oxygen at a rate of R or P g/m^2/d. No water is flowing into or out of the compartment and oxygen goes into the column of water above the bed, so the effective rate of *R* and *P* is the rate of oxygen respiration and production, respectively at the bed times the depth of water. Thus if the depth changes, *R* and *P* in $g/m^2/d$ doesn't change but *R* and *P* in the compartment above the bed does change, with the new respiration and production equal to the respiration and production at the bed in $g/m^2/d$ multiplied by the new depth Y (m), to give compartment respiration and production in units of $g/m^3/d$. Thus, the respiration rate *R* is directly proportional to stream depth *Y*:

$R = R_{ref} * Y_{ref}/Y$ ....(6)

where R_{ref} is the re-aeration rate at the reference depth Y_{ref}.

Photosynthetic production is adjusted in the same manner, thus retaining a constant ratio of average production to respiration (*P* over *R*).

The reference flow and the corresponding values of velocity and depth are also used to establish a reference re-aeration coefficient (k_{ref}) so that the re-aeration coefficient (k) may be calculated for another flow with an associated reference velocity (V_{ref}) and depth (Y_{ref}) according to:

$k = k_{ref} * (V_{ref})^{0.5} / (Y_{ref})^{1.5}$ (7)

Recent studies of re-aeration rates in New Zealand streams has shown that re-aeration does not necessarily vary according to equation 7. The program has an option that prevents the adjustment of re-aeration for flow.

Date of oxygen measurements

The date (dd/mm/yy) of the measurement of diurnal oxygen variation is used to calculate the photoperiod (hours of day light and solar noon). The times of solar noon, sunrise and sunset and daylight hours are calculated from the date, latitude and longitude. Local times are set by specifying the time difference between local time and GMT using the menu “Set time zone and location”.

Latitude and longitude

The latitude and longitude affect the hours of day light and time of solar noon. The latitude and longitude can be set using the menu “Dissolved Oxygen>>Set time zone and location” or they can be set when fitting parameters and modeling the variation of minimum DO with flow.

Time lag between DO deficit minimum and solar noon.

The time lag between the minimum dissolved oxygen deficit and solar noon is estimated by fitting a cosine to diurnal oxygen variation. Generally, it will be necessary to examine a number of periods of 24-h to determine the best parameters.

Daylight hours are for a level horizon and do not allow for hills or mountains obscuring the horizon. If times are specified as daylight saving time, 1 hour is subtracted to give standard time. All graphs and results are in standard time.

Note that there is no solution to delta method when the lag time is less than or equal to zero or when the lag time exceeds about 5.3 hours. If this occurs, the lag time from solar noon is highlighted in red and re-aeration is assumed to be either 0.1 per day (when lag time > 5.3) or 300 per day when lag time <= 0.

Variations in sunlight, such as sunshine in the morning and cloud at mid-day and in the afternoon can cause maximum DOD to occur before solar noon. Usually these instances are infrequent and if consistent may be caused an incorrect time on the DO recorder.

Time lags of greater than about 5.3 hours could also be caused by variations in sunshine, with afternoon sun and morning cloud. However, if long time lags occur frequent in the measured DO data, it may indicate that the single station assumption of uniform upstream conditions is violated. For example, if the recording site is downstream of the section of river where macrophyte densities are highest, the travel time between the macrophytes and recording location can increase the apparent lag time.

DO deficit range

The DO deficit (DOD) range is the difference between the maximum and minimum dissolved oxygen deficit recorded over a 24-h period. The DO deficit range is the same as the range of dissolved oxygen concentrations adjusted to a constant temperature through the day.

The diurnal range of DOD is calculated as the difference between the 1 hour average maximum and 1 hour average minimum. The one hour values are based on 5 minute values interpolated over the daily DOD record. A 1 hour average is used to minimize the effects of spikes in DOD record.

Average daily DO and DOD

This is the daily average of dissolved oxygen concentration and deficit calculated as a time weighted average to allow for datasets with a variable time interval.

$$DO = \frac{\sum_{i=0}^{1}\left[(t_{i+1}-t_i)\times\frac{DO_{t_i}+DO_t}{2}\right]}{\sum_{i=0}^{1}(t_{i+1}-t_i)} \quad (8)$$

Where t is time as a fraction of day and DO is oxygen concentration at time i.

Daily mean water temperature

The daily mean water temperature is the average water temperature in °C over the day on which the average DO, DOD and DO range were measured. The average temperature is the time weighted average (e.g., equation 8) to allow for datasets with a variable time interval. This temperature is used to standardize values of re-aeration coefficient and respiration rate to 20°C.

Re-aeration coefficient

The stream re-aeration coefficient inferred from a single-station diurnal oxygen curve analysis is a function only of the photoperiod duration and of the time lag between solar noon and oxygen maximum. It is independent of rates of primary production and respiration.

The re-aeration coefficient *k* quantifies a stream's capacity to exchange oxygen with the atmosphere. It is a "first-order" coefficient, meaning that the overall rate of re-aeration (or de-aeration in super-saturated conditions) is proportional to the oxygen deficit (or surplus), with the coefficient being the constant of proportionality. The process it describes is not connected to other biologically mediated processes and is commonly approximated by functions of velocity, depth and slope.

Streams that are slow flowing with aquatic macrophytes will have low *k* values and, correspondingly, large diurnal variations in DO. If the respiration rate is also high then we can expect low daily DO minima during summer low flows. The most accurate way of measuring *k* is by the gas tracer method but this can be labor intensive.

When using field measurements to establish dissolved oxygen parameters, the following exact equation (McBride & Chapra 2005) is solved for k_a:

$$\pi\cos\left[\pi\left(\frac{1}{2}+\frac{\varphi}{f}\right)-\theta\right]-k_a f\gamma e^{-k_a\left(\varphi+f/2\right)}=0 \qquad (9)$$

where k_a is in reciprocal days, *f* the photoperiod is the day length, and φ the time lag is the time between noon and the dissolved oxygen deficit minima.

Gamma γ is given by:

$$\gamma=\sin\left(\tan^{-1}\frac{\pi}{k_{af}}\right)\left[\frac{1+e^{-k_a(T-f)}}{1-e^{-k_a T}}\right] \qquad (10)$$

where $T = 1$.

or by the approximation (McBride & Chapra 2005)

$$k_a=7.5\left[\frac{5.3\left(\frac{f}{14}\right)^{0.75}-\varphi}{\varphi\left(\frac{f}{14}\right)^{0.75}}\right]^{0.85} \qquad (10)$$

The re-aeration coefficient (k_a) is adjusted to the 20°C reference temperature using equation 4, and optionally is also adjusted for the depth and velocity to a reference flow using equation 7.

Wilcock (1982) measured re-aeration coefficients in a number of Waikato streams and developed a modified form of equation based on the O'Connor-Dobbins equation (O'Connor

& Dobbins 1956, 1958). This modified form[8] (Wilcock 1984a&b) was corroborated by Wanninkhof *et al.* (1990) and is:

$$k_a^{(20)} = 5.24\sqrt{\frac{V}{Y^3}} \quad (5)^9$$

where V is reach-average velocity (m/s) and Y is reach-average depth. This equation is often appropriate for New Zealand streams.

Daily production/respiration ratio

The daily production/respiration ratio (P/R) is the total production of oxygen by photosynthesis over a 24-hour period divided by the total consumption of oxygen by respiration in that period. It is thus the daily average ratio of the rates of these two processes, with "daily" meaning 24-hours.

An analysis of 28 Waikato lowland streams found $R^{(20)}$ values between 3.5 and 55.0 g O2/m^3/day, and P/R values between 0.07 and 1.87. Four main groups of streams were identified in this analysis and the mean values for these groups provide some general guide for estimating values of $R^{(20)}$ and P/R .

1. Deep streams with low shade and slow-flowing water: $R^{(20)}$ 10; P/R 1.0
2. These streams were typically wide, deep (>1m) and sluggish with moderate plant biomass. They were considered particularly susceptible to small reductions in flow and have a high risk of DO deficit stress.
3. Deep streams with low shade and moderate-flowing water: $R^{(20)}$ 38; P/R 0.4
4. These streams typically had high plant biomass and high amounts of decomposing organic matter. Mean depths were usually >0.8 m. Higher current velocities allowed for higher than average re-aeration. These streams were considered to have a moderate risk of DO stress.
5. Streams with high shade and low-moderate depths: $R^{(20)}$ 8; P/R 0.3
6. These streams typically had low plant biomass due to shade often provided by riparian trees, and mean depths <0.8 m. They were considered to constitute a low DO stress risk, although low re-aeration during droughts could reduce night time DO levels.
7. Streams with low-moderate shade and low-moderate depths: $R^{(20)}$ 24; P/R 0.2

These Waikato streams were typically cool and had high respiration rates indicating large amounts of decomposing organic matter. Re-aeration was high indicating moderate-fast current velocities and low-moderate mean depths (<0.8 m). They were considered to have a low risk of incurring large DO deficits.

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[8] Wilcock's amendment was to raise the proportionality constant in the formula of O'Connor & Dobbins by 40%, to 5.24—similar findings were later reported by Wanninkhof *et al.* (1990).

23.4 Reach and network models

The reach (single station) DO model applies to streams with a reasonably homogenous distribution of aquatic plants (which can include algae) in a reach. Three main assumptions are invoked:

- a single reach analysis is appropriate - this assumes that while DO at a site exhibits substantial time variation, at any time spatial gradients of DO along the stream are minimal. This is tenable if there is a homogenous distribution of plants over a reach upstream of the site.
- the mass of plants present is not affected by changes in the low flows - this means that rates of photosynthesis and respiration per square metre of stream bed are constant.

According to Chapra & Di Toro (1991), the assumption that any time spatial gradients along the stream are minimal is tenable if there is a homogenous distribution of plants over a reach at least $\frac{259V*}{k_a}$ kilometres upstream of the station, where *V** is the reach-average velocity (m/s) and k_a is the reach re-aeration coefficient (d^{-1}).

The network (multiple station) procedure calculates dissolved oxygen concentration and biological oxygen demand (BOD) along a river and can include inflows from tributaries, point source discharges and outflows (abstractions).

Six processes are modeled to calculate DO along a section of river. These are tributary inflows (flow, DO and BOD), outflows (abstractions), longitudinal advection (downstream transport by the water current), longitudinal dispersion (the way in which DO and other constituents of the water spread out longitudinally as they flow downstream), re-aeration (interchange of oxygen between water and atmosphere), and aerobic bacterial decomposition.

The model follows the usual Streeter-Phelps assumptions. For each time step, the change in *BOD* was:

$$\Delta BOD = -k_1 BOD$$

Where k_1 is river deoxygenation rate per time step. The equivalent change in dissolved oxygen is:

$$\Delta C = k_2(C_{sat} - C) - \alpha k_1 BOD$$

Where k_2 is the river re-aeration rate, C_{sat} is dissolved oxygen saturation concentration, *C* dissolved oxygen concentration, and α alpha is the ratio of ultimate BOD to five-day BOD[10] ($BOD_{ultimate}/BOD_5$).

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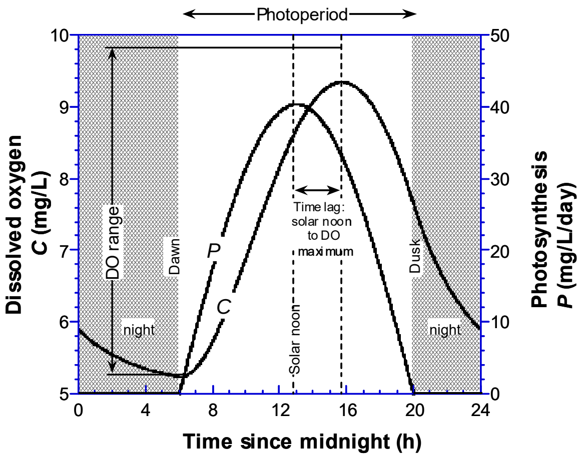
[10] BOD_5 is the bacterial oxygen demand measured over 5 days.

23.5 Reach model

The reach (single-station) procedure calculates dissolved oxygen (DO) as a function of stream flow at the downstream end of a reach. This minimum, which occurs a little after dawn, is the result of night-time consumption of oxygen by the respiration of bacteria and plants in the reach between the abstraction point and the equilibrium site. During the day photosynthesis by plants causes the DO to rise again, and so, all other things being equal, the diurnal cycle is identical from one day to the next.

A relatively uniform distribution of aquatic plants is assumed to be present in the reach. Depending on stream velocity and depth that reach may need to be rather long. If the actual reach containing the plants is too short, the minimum DO at the end of the reach will not be accurate. Diurnal curve analysis can be used to determine these parameter values using a simple, direct analytical solution procedure advanced by Chapra & Di Toro (1991), and explained in McBride & Chapra (2005).



The parameters are usually adjusted to a water temperature of 20°C using standard formulae. This enables a simple comparison of parameters between streams.

Accurate estimates of the parameters describing the three fundamental processes are essential for prediction of dissolved oxygen and this program allows these parameters to be determined from field measurements, rather than estimated. However, in some streams it may be possible to estimate oxygen parameters (k, R and P) based on experience.

23.5.1 Open DO file and Calibrate

DO Model provides an automatic procedure to calculate the dissolved oxygen parameters each day from field measurements of DO and water temperature.

The input data for fitting parameters to field data is columns of data containing the date/time, dissolved oxygen concentration, and water temperature. The date/time can be in either daylight saving time or standard time. The data can be at unequal time intervals but should be sufficiently frequent to define that shapes of the diurnal curves. If times are specified as daylight saving time, 1 hour is subtracted to give standard time. All graphs and results are in standard time.

The times of solar noon, sunrise and sunset and daylight hours are calculated from the date, latitude and longitude. Local times are set by specifying the time difference between local time and GMT using the menu “Set time zone and location”.

The diurnal measurements of DO (mid-night to mid-night) and water temperature are used to calculate the oxygen deficit (*DOD*) for a dissolved oxygen concentration *DO* at a temperature *T* at each time t during the day:

$$DOD = C_{sat}(T) - DO \quad (1)$$

where $C_{sat}(T)$ is the saturated dissolved oxygen concentration at time t and temperature *T* calculated using equation 2.

The saturation concentration of oxygen in sea-level freshwater (denoted by C_{sat}) is given by the formula of Benson & Krause (1984—assuming zero salinity and standard atmospheric pressure):

$$C_{sat} = e^{-139.34411 + 1.575701\times10^{5} Z - 6.642308\times10^{7} Z^{2} + 1.243800\times10^{10} Z^{3} - 8.621949\times10^{11} Z^{4}} \quad (2)$$

where $Z = \frac{1}{T + 273.16}$ is reciprocal absolute water temperature.

A cosine (equation 3) is fitted to DOD by non-linear least squares to the recorded DO and temperature between sunrise and sunset. The phase shift of the fitted cosine (*theta*) gives an estimate of time lag between solar noon and minimum DOD.

$$DOD = beta + alpha \times \cos(2 \times pi \times t + theta) \quad (3)$$

where *t* is a fraction of the day, *beta* is the average *DOD* and *alpha* is the amplitude of the diurnal variation.

The DOD minimum should always occur after solar noon for correct calculation of oxygen parameters. Solar noon is the mid-point between sunrise and sunset.

The diurnal range of DOD is calculated as the difference between the 1-hour average maximum and 1-hour average minimum. The one-hour values are based on 5-minute values interpolated over the daily DO record. A 1-hour average is used to minimize the effects of spikes in DOD record.

The daily average DOD is calculated as the time weighted mean so that data can be at unequal time intervals.

The DO parameters are calculated for the daily average temperature (Tav) from the lag time, daylight hours, daily mean DO to adjusted Tav, and Q_{10}, the ratio of respiration rates 10°C apart. The program calculates parameters either with the approximate delta method of McBride and Chapra (2005) or by solution of the delta equations given in McBride & Chapra (2005) using numerical methods (regula falsi). If the numerical methods fail, McBride’s approximations are used.

Note that there is no solution to delta method when the lag time is less than or equal to zero or when the lag time exceeds about 5.3 hours. If this occurs, the lag time from solar noon is highlighted in red and re-aeration is assumed to be either 0.1 per day (when lag time > 5.3) or 300 per day when lag time <= 0.

Variations in sunlight, such as sunshine in the morning and cloud at mid-day and in the afternoon can cause maximum DOD to occur before solar noon. Usually these instances are infrequent and if consistent may be caused an incorrect time on the DO recorder.

Time lags of greater than about 5.3 hours could also be caused by variations in sunshine, with afternoon sun and morning cloud. However, if long time lags occur frequent in the measured DO data, it may indicate that the single station assumption of uniform upstream conditions is violated. For example, if the recording site is downstream of the section of river where macrophyte densities are highest, the travel time between the macrophytes and recording location can increase the apparent lag time.

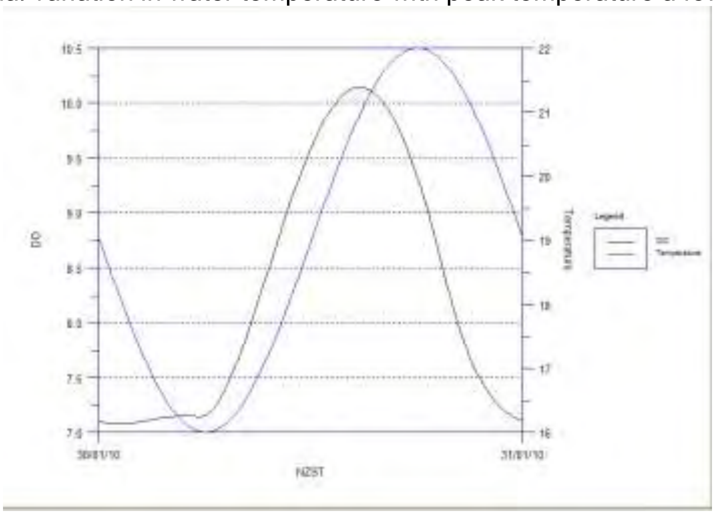
The parameters are adjusted to 20°C using the daily mean temperature and equations 4 & 5.

How to calibrate the Reach model

The program automatically detects date/time variables and you select the appropriate date/time variable by highlighting it and clicking the arrow button to transfer it into the date/time box on the right of the screen. Radio buttons allow you to specify whether the data are to Standard time or Daylight-saving time (1 hour less than standard time). Now select the variable representing dissolved oxygen concentration DO, and click the arrow button to transfer it to the DO box on the right. Select the temperature variable in the same way. There is no flow variable so leave the right Flow box empty. If no temperature variable is selected, a constant 20°C temperature is assumed.

Press the OK button.

3. The data will now be displayed in the tab headed DO data plot. This plot shows the diurnal variation in water temperature with peak temperature a few hours later than peak DO.



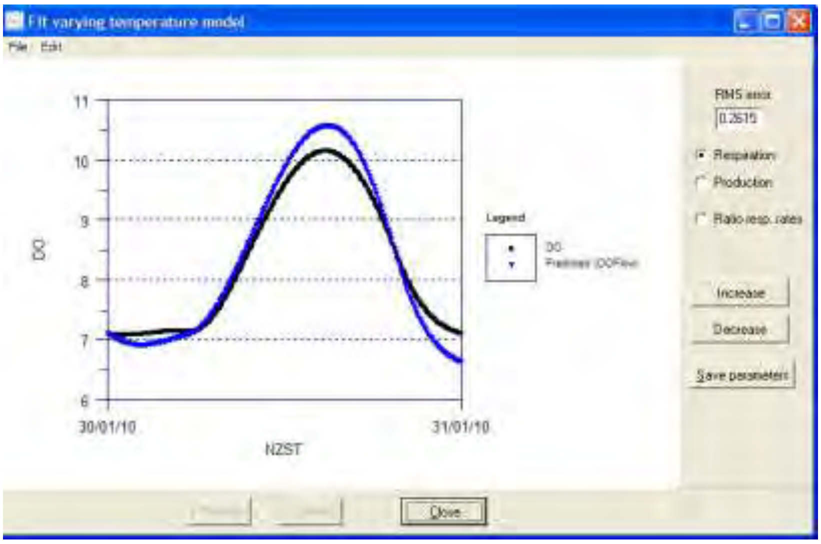
4. Now that we have some data, press the Fit parameters button or use menu Analysis/Fit parameters. A dialogue box is displayed that allows you to specify the site location (latitude and longitude) that is used to calculate times of sunrise and sunset for the dates in the data file. The ratio of respiration rates 10 degrees apart can also be altered, but 2 is a good starting value. Fitting can be done by either the approximate delta method or the numerical solution to the delta method. Similar results are obtained by both methods, but the numerical solution gives a slightly better fit to measured data in most situations. Use the default setting – use numerical solution - and press the OK button.

5. The parameters are now fitted and to see them, select the tab headed DO parameters.

Data | DO Parameters | DO data plot

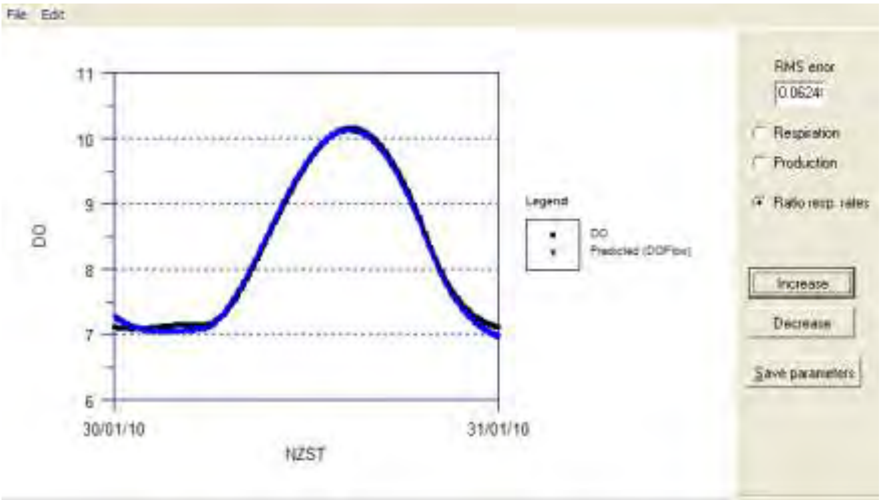
Date	Daily mean DO (mg/L)	Daily mean DO deficit (mg/L)	DO deficit range (mg/L)	Time lag between DO deficit min and solar noon (h)	Daily mean temperature Tav (deg C)	Daily mean flow (L/s)	Reaeration coefficient at 20C (/d)	Daily respiration rate at 20C (g/m3/d)	P/R ratio	Ratio respiration rates 10C apart	Root mean square error
30/01/10	8.29475	0.99513	3.97672	2.72964	18.99985		7.08792	21.30469	0.65351	2.00000	0.01142

These parameters were calculated using the delta method and are the starting values used in the fitting procedure for the varying temperature method. There is a button under the parameters labeled Fit parameters with temperature varying model (DOFlow) “Fit parameters with temperature varying model (DOFlow)”. Press this button to display the Fit varying temperature model window. Initially, this shows the “measured” data and data predicted with the current DO parameters.



The procedure is one of trial and error adjustment of respiration, production and ratio of respiration rates to get the values that give the best fit. Once these are obtained the values are Saved back onto the DO Parameters tab.

The RMS error is displayed to give a measure of best fit, and fitting can be achieved by reducing this to a minimum. First, increase respiration, to see if that decreases the rms. If so, increase respiration further until it bgins to increase, then decrease once. Now, select the radio buttion Production and increase/decrease production until a minum rms is found. Repeat that procedure with the ratio of respiration rates. Slect the radio button Respiration and repeat the whole cycle until no further reduction in RMS error can be achieved. In this example, the RMS error was reduced from 0.2615 to 0.0624. At this stage, save the parameter values to the DO parameters tab and close the window.



6. The fitted parameters can now be used to model the variation in DO with flow by pressing the Model DO button or selecting menu Analysis/Model DO. The dialogue that is displayed allows you to view how the fitted daily parameters fit the measured data, for the whole period of record.

To model the variation of DO with flow in a river, we must know how the depth and velocity vary with flow. This information is contained in a SEFA file. For each row of parameters, DO is predicted over the period of record (as displayed in the graph DO data plot) and the root mean square (rms) calculated by comparison with the measured data. Hence, the rms value gives some indication of the parameter set that provides the best fit to the period of record.

The variation of DO with flow can be calculated with or without the assumption the re-aeration varies with flow by checking the checkbox “Assume constant re-aeration coefficient”. In this example, check this checkbox so that the re-aeration coefficient is not adjusted for flow changes.

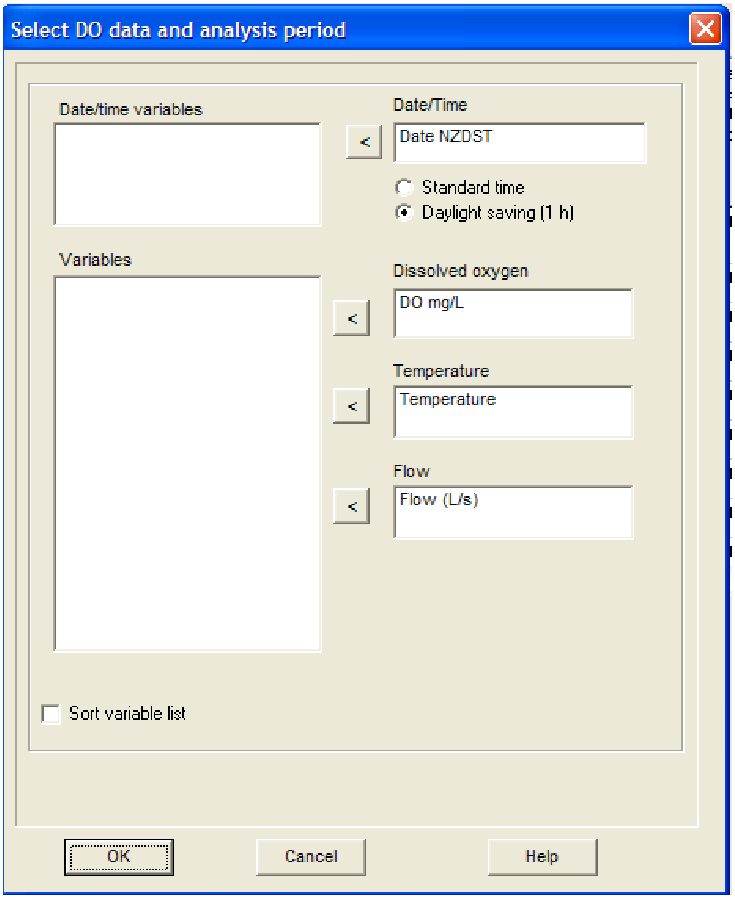
If you select a row without entering a reference flow in column 6, you receive the message “Enter reference flow”. Enter the flow in column 6, 500 in this example and press the OK button.

Example - some real data analyzed

1. Open a data file by clicking the button labeled Open file…, using the menu File>>Open file… or selecting from the files listed by the menu File>>ReOpen. Open the file TopehaehaeExample.csv.

2. The tab headed data, now shows the contents of that worksheet and you must select the relevant DO data from that sheet, by clicking the Select variables button (now enabled) or by menu Analysis>>Select variables.

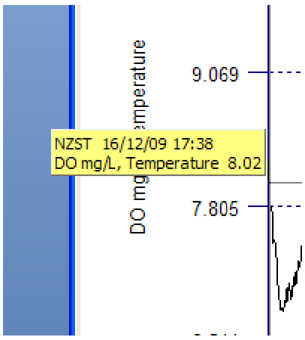
The program automatically detects date/time variables and you select the appropriate date/time variable by highlighting it and clicking the arrow button to transfer it into the date/time box on the right of the screen. These data are to daylight saving time, so check the radio button labeled Daylight saving time (1 hour less than standard time). Now select the variable representing dissolved oxygen concentration DO mg/L, and click the arrow button to transfer it to the DO box on the right. Select the temperature variable in the same way. Select the flows variable, Flow L/s, and click the arrow button to transfer it to the flow box.



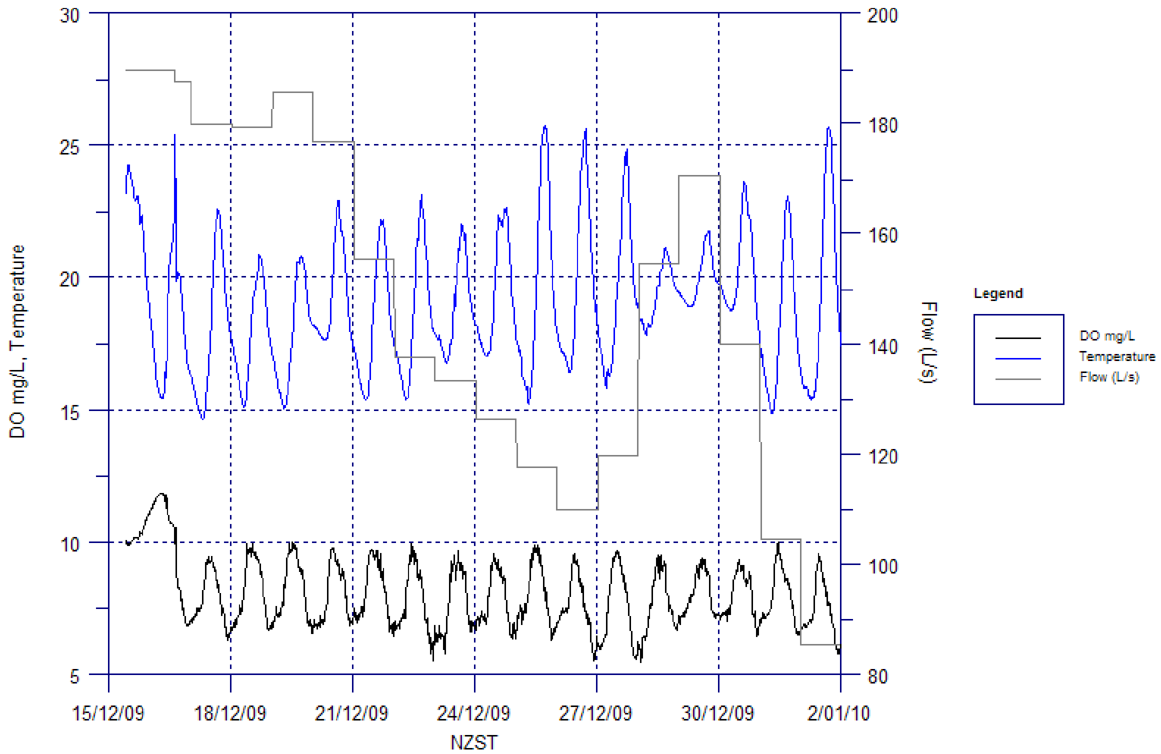
Press the OK button.

3. The data will now be displayed in the tab headed DO data plot. This plot shows DO, water temperature and flow. DO recorders are usually started in air a day or so before they are installed in the stream. This record was started on the 15 January and was installed on 16 January at 14:15.

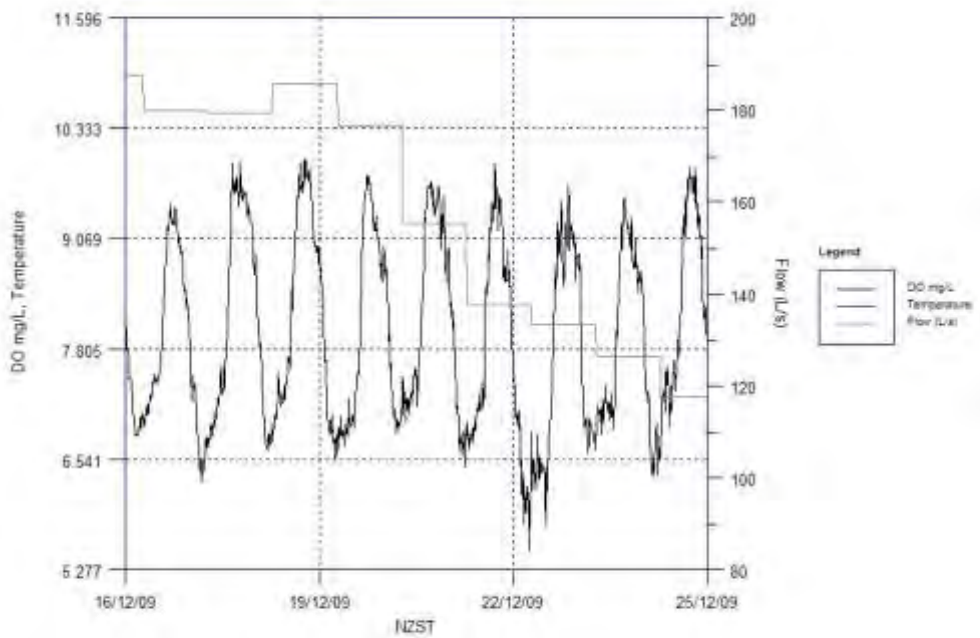
You can see where this time is by clicking on the graph and while you hold the mouse button down the Data/time and Y value is displayed.



There is no need to remove these data that record atmospheric conditions from the record before using it in SEFA. The data to be analyzed can be selected in SEFA by using the zoombtn or the menu Edit/Zoom.



Click the zoom button and the cursor changes to a pointing hand. Locate the cursor over the point where you wish to start the analysis, press the right button and holding the cursor down move the zoom rectangle to the right to the point where you want to end the analysis. Release the right mouse button and the graph will be displayed over the selected time period. Select the period of data from 16/12/09 17:40 to 25/12/09 15:45.



4. Now that we have selected the data, press the Fit parameters button or use menu Analysis/Fit parameters. A dialogue box is displayed that allows you to specify the site location (latitude and longitude) that is used to calculate times of sunrise and sunset for the dates in the data file. The ratio of respiration rates 10 degrees apart can also be altered, but 2 is a good starting value.

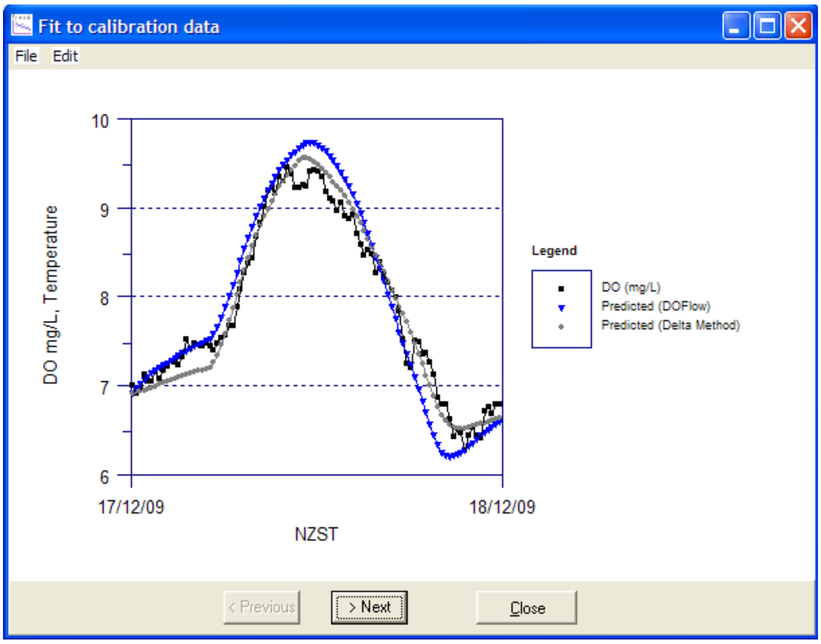
5. The parameters are now fitted and to see them, select the tab headed DO parameters.

Data | DO Parameters | DO data plot

Date	Daily mean DO (mg/L)	Daily mean DO deficit (mg/L)	DO deficit range (mg/L)	Time lag between DO deficit min and solar noon (h)	Daily mean temperature Tav (deg C)	Daily mean flow (L/s)	Reaeration coefficient at 20C (/d)	Daily respiration rate at 20C (g/m3/d)	P/R ratio	Ratio respiration rates 10C apart	Root mean square error
17/12/09	7.85966	1.62648	3.20006	0.81331	18.02213	179.66813	30.61898	97.34952	0.44026	2.00000	0.61361
18/12/09	8.17140	1.33203	3.44677	1.17244	17.86409	179.34292	21.02886	63.33809	0.51262	2.00000	0.48927
19/12/09	8.23251	1.28030	3.52775	1.18848	17.82859	185.58245	20.74558	62.19123	0.52857	2.00000	0.51963
20/12/09	7.98064	1.24810	3.49983	1.40454	19.30370	176.38906	16.72513	46.46415	0.53628	2.00000	0.57090
21/12/09	8.16629	1.24962	3.76842	1.35070	18.35257	155.10823	17.85603	53.85694	0.55344	2.00000	0.67211
22/12/09	7.70670	1.67302	4.32106	0.40412	18.54861	137.55698	61.32992	221.61299	0.50539	2.00000	0.79821
23/12/09	7.68692	1.61867	4.49595	1.52604	18.88264	133.12438	15.40623	56.55854	0.53609	2.00000	0.68181
24/12/09	7.79491	1.40957	3.61499	0.97226	19.45296	126.27354	24.63117	72.34512	0.50799	2.00000	0.70541
25/12/09	7.99715	1.20727	3.90518	0.96135	19.59768	117.35979	24.83464	70.27562	0.56548	2.00000	0.84278

View fit to calibration data

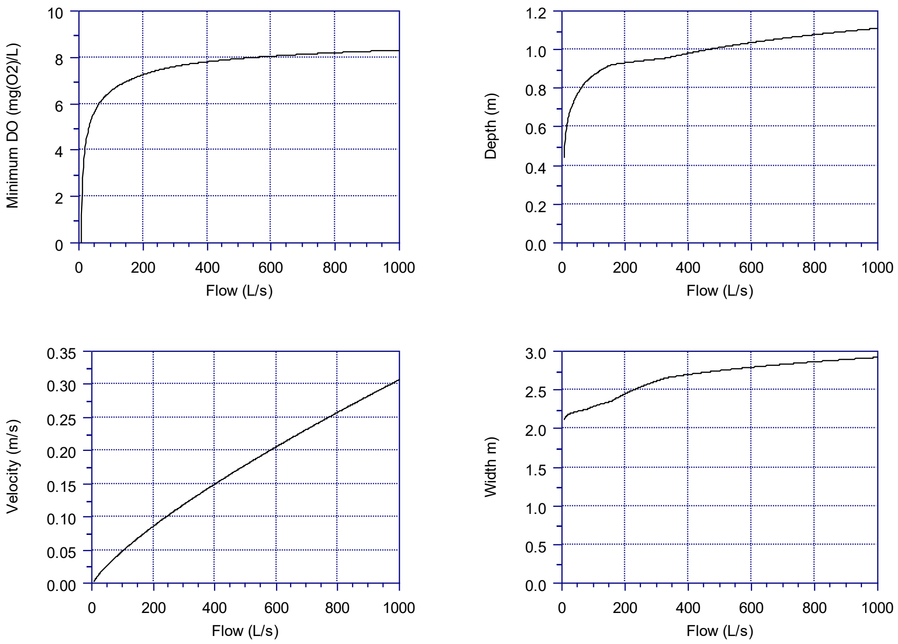
These parameters were calculated using the delta method and listed for each 24 hours (midnight to midnight period in the selected period of record. The RMS error is displayed on the right hand side to give an idea of the goodness of fit. However, a better method of seeing how well the model fits the daily daya is to press the button under the parameters labeled “View fit to calibration data”. This will display the Fit to calibration data window. Initially, this shows the “measured” data and data predicted with the DO parameters for the first day. There are two arrow buttons at the base of this window. These can be used to scroll through the calibration fits and parameters for each day in the selected period.



5. The fitted parameters can now be used to model the variation in DO with flow by pressing the Model DO button or selecting menu Analysis/Model DO. This dialogue can take a while to display because it calculates the mean daily temperature and time of temperature maxima and minima for each day the selected record and lists the median values in the dialogue. It also simulates DO using each set of the parameters listed for the selected period of record. This gives a measure of how well the parameters fit, overall.
6. The user can elect to use either the median of all calculated parameters, the mean of all calculated parameters or any of the values for the days modeled.

To model the variation of DO with flow in a river, we must know how the depth and velocity vary with flow. This information is contained in a SEFA file. The variation of DO with flow can be calculated with or without the assumption that re-aeration varies with flow by checking the checkbox “Assume constant re-aeration coefficient”. In this example, uncheck this checkbox so that re-aeration is adjusted for flow changes.

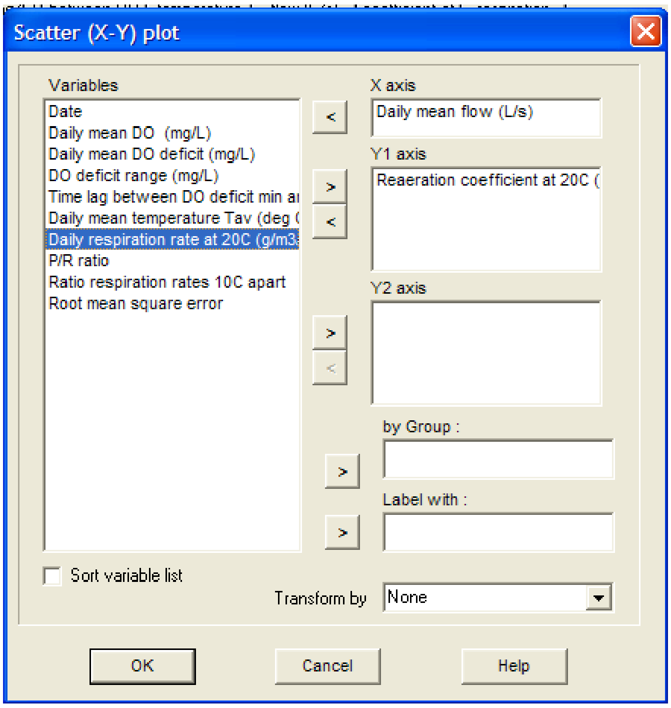
7. The results are now displayed on the tab headed Results.

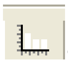


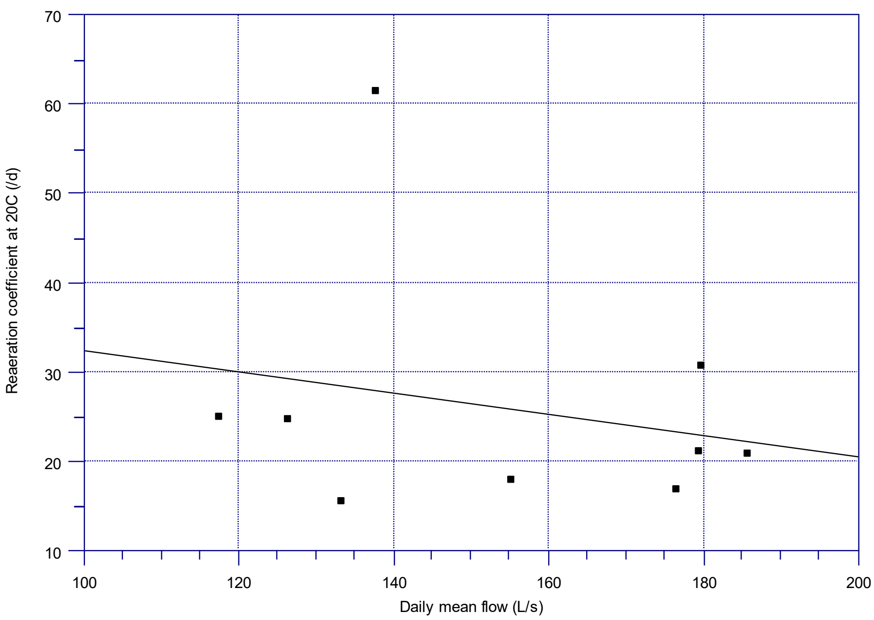
Any of these graphs can be displayed enlarged in its own window by double clicking on the graph. Right clicking will get a popup menu for copy or graph options. Graph display options (text, color, axes etc.) can also be changed in Edit/Display>>Graph options.

8. The variation of oxygen parameters can be examined because the data file contained flows. To examine how the parameters vary with flow, select the tab headed DO Parameters. Now select the menu Analysis/X-Y plot.

A dialogue will be displayed that lists all the variables listed on the DO Parameter spreadsheet. Select the variables Daily mean flow (L/s) for the X-axis and Re-aeration coefficient at 20C for the Y-axis and press OK.



The points on the graph are the daily mean flows and the calculated re-aeration constant on that day. Trend lines can be fitted to these points, by pressing the graph options button  or selecting the menu Edit/Display>.Graph options. A curve or regression line can then be selected and fitted to the points. The regression equation and variance explained (r^2) is shown in the messages tab and the line or curve is plotted on the graph. In this case, there is no indication that re-aeration decreases with flow; in fact, there is a slight decrease in re-aeration as flow increases. In the modeling above, we assumed that re-aeration varied with flow, and repeating the analysis assuming a constant re-aeration rate will show that this was a conservative assumption.



23.6 Reach prediction

This menu item incorporates the calibration and prediction of dissolved oxygen. Field measurements taken on one day can be entered and DO parameters will be calculated automatically. Alternatively, parameters can be entered directly. Predictions of DO (minimum, mean and maximum daily) are made over the specified range of flows using these parameters for a specified date and water temperature.

23.7 Dissolved Oxygen References

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Chapra, S.C.; Di Toro, D.M. (1991). Delta method for estimating primary production, respiration, and reaeration in streams. *Journal of Environmental Engineering 117(5)*: 640-655.

Elmore, H.L.; West, W.F. (1961). Effect of water temperature on stream reaeration. *Journal of the Sanitary Engineering Division of the American Society of Civil Engineers 87(SA6)*: 59-71.

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McBride, G.B.; Cooke, J.G.; Donovan, W.F.; Hickey, C.W. Mitchell, C.; Quinn, J.M.; Roper, D.S.; Vant, W.N. (1991) Residual flow and water quality studies for the Ararimu (Campbell Road) water supply scheme. DSIR Marine and Freshwater Consultancy Report 6018. Report to Auckland Regional Council (Operations Division). 57 p.

O'Connor, D.J.; Dobbins, W.E. (1956). The mechanism of reaeration in natural streams. *Journal of the Sanitary Engineering Division of the American Society of Civil Engineers 82(SA6)*: 1-30.

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Wanninkhof, R.; Mulholland, P.J.; Elwood, J.W. (1990): Gas exchange rates for a first-order stream determined with deliberate and natural tracers. *Water Resources Research 26(7)*: 1621-1630.

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24 Water surface profile modeling of rivers

24.1 River model

The basic stream geometrical unit is a cross-section. A reach of river is a number of cross-sections that represent significant channel characteristics. Each cross-section is described by a distance from the downstream cross-section and a set of offsets and levels that describe the ground surface.

The levels can be specified as a depth below or above water level or as levels. All levels must be to the same datum.

24.2 Modeling procedure

River modeling is a step-by-step procedure:

- checking data
- model calibration
- water surface profile (WSP) calculation

A survey is made of the channel and waterway at one or more flows. These data are used to calibrate a model of the stream reach that can then be used to predict water levels at other flows.

Much of the calibration is automatic using default assumptions. The calibration should be checked and can be altered if required.

The series of predicted water levels are then used to develop stage-discharge relationships for each cross-section.

Analysis of habitat (IFIM) or hydraulic characteristics can then be made for a range of flows.

25 WSP - field survey requirements

The survey and analysis of rivers using water surface profile modeling can be difficult, especially in steep or small streams. The alternative procedure is to develop stage discharge curves for each cross-section and to weight each section by the proportion of channel length it represents (habitat weighting percentage). This alternative method usually results in more accurate predictions of water levels and a survey that may be more representative of average conditions in the river because it can encompass all habitat types over a longer section of river.

Hydraulic modeling or simulation uses the Manning equation and the standard step method ("Open Channel Flow", Henderson 1966) to predict the water surface profile for a given flow.

After selecting the channel to be surveyed, a series of cross-sections are marked out and surveyed.

Habitat surveys will usually require more closely spaced cross-sections than flood flow modeling where sections can be further apart because the flow is uniform.

Flows should be constant while water surface profiles are surveyed.

Varying flows make subsequent analysis of friction losses difficult. However, if a flow change occurs during a survey, it is possible to calibrate a hydraulic model based on the varying flows throughout the reach.

Cross-section and offset location and spacing determine how accurate the hydraulic model will be. If location and spacing is appropriate to the variability of the gradient and cross-section area there should be little difficulty in calibrating the hydraulic model.

26 Reach location and cross-section spacing

Usually reaches are selected so that they represent the character of a longer section of the river. Changes in river gradient and flow often indicate a change in river character.

26.1 Cross-section spacing and location

Cross-sections should be spaced so that cross-section area, width, and velocity vary uniformly between cross-sections. Cross-section spacing will therefore decrease as the variability of the stream geometry increases.

Cross-section spacing should decrease where the water surface slope is constant. Large changes in water surface slope between pairs of cross-sections should be avoided.

The water surface across the section should be as near to horizontal as possible. To do this, the cross-section need not be in a straight line, and can curve or kink to follow features such as diagonal riffles. This should maintain a constant height difference between all points on the section and the adjacent sections.

Usually cross-sections should be at right angles to the flow but sometimes the requirement to have a horizontal water surface may mean that the flow in all or part of the section is not at right angles. Minor deviations can be tolerated but if a large part of the flow is not at right angles, the offset distances can be reduced according to the current angle before processing the data. Failure to do this will result in an excessively large measured flow for the section and incorrect hydraulic characteristics for the section.

Cross-sections need not be parallel to each other.

Ideally, the distance between cross-sections is measured along the thalweg. However, this is usually measured along one bank, or when cross-sections are not parallel, the average of the distance between cross-sections measured along each bank.

26.2 Downstream section water level

The relationship between water level and flow at the downstream cross-section gives starting levels from which the upstream water surface profile can be calculated. The stage-discharge relationship is best established by recording water levels for a number of flows in the same way as ratings are established for water level recorder staff gauges (see hydrology texts such as "Applied Hydrology" by Linsley, Kohler and Paulhus).

Water levels at the downstream section are measured from either a fixed peg or temporary staff.

26.2.1 Variation of Manning n with flow

This describes the calculation of Manning's N for cross-sections and should not be confused with the values of Manning's N at points across the cross-section, as used in IFG4 emulation.

Manning's n is calculated from each gauging:

*Flow = 1/N*A*R^2/3*S^1/2*

assuming that the slope is constant.

The variation of Manning n with flow for the rating is calculated according to the equation:

N = a Flow^b

Usually Manning's n increases as flow decreases so that b is negative. Water levels at other flows are calculated in the reverse manner, by first calculating b from the flow and then calculating the water level from Manning’s equation.

The variation of n with flow can be used in the calculation of water surface profile, as well as to determine an appropriate starting level. If measurements of flows and levels are made at each cross-section, they are used to calculate the variation of n with flow at each cross-section. This improves the accuracy of water surface profile modeling, especially at low flows.

27 Water surface profile analysis

Water surface profile modeling begins with calibration of the model. This involves making small adjustments to the level of the cross-section or specifying eddy loss coefficients (bend, contraction, and expansion) so that reasonable values of Manning's n are calculated for the observed (calibration) water surface profile.

After calibration, water surface profiles can be calculated for any flow from a starting level at the downstream section.

27.1 WSP method

Initially, the longitudinal profile of the reach is displayed on the screen, showing the water level, mean bed level, and optionally the minimum bed level and minimum bank level.

When the Model button is pressed, a dialogue box appears in which the starting level and flow can be specified.

The water surface profile is calculated using the standard step method. The calculation proceeds in an upstream direction using the level at the downstream section as the starting point. The profile is displayed in yellow.

There is no limit on the maximum water level at any cross-section and hydraulic properties are extrapolated depending on the bank slope. The minimum bank level can be displayed to check whether calculated water levels are based on extrapolated cross-section properties.

A water surface profile can be saved and used to develop rating curves at each cross-section. When the save button is pressed the profile is drawn in black and will be displayed when other flows are modeled. When 2 or more flows are modeled and saved, you will be asked whether to calculate rating curves on closing the window.

27.1.1 Starting level and downstream cross-section

The starting level for the flow to be simulated can be specified or, by default, is determined from the selected rating curve at the downstream section.

The WSP calculation can begin at a section upstream of the downstream cross-section.

The starting level is checked to ensure that it is not less than the minimum cross-section level, stage of zero flow, and the water level for critical flow at the section.

27.1.2 Extrapolation of cross-sections

If the water level is above the highest point surveyed then linear extrapolation is used to estimate the water's edge if the bank slope is greater than 1 in 20. If the slope is less than this, a vertical bank is assumed 0.01 m from the last point surveyed.

27.1.3 Mean bed level

In the water surface profile display, the mean bed level is the water surface level less the mean water depth (cross-section area divided by width) and the maximum depth is the water surface level less the maximum water depth at the cross-section.

27.1.4 Interpolated cross-sections

Usually, a WSP is calculated without interpolated sections.

The predicted profile should be parallel to the measured profile. However, if not and water levels appear unusually high at the upstream end of a convex slope (the head of a riffle) then the calculation should be retried using 1 or more interpolated sections.

When the bed profile is convex, the predicted water level can be overestimated, because the average energy slope is overestimated.

27.1.5 Variation of flow between cross-sections

If the vary flow box is checked, the flow at each cross-section can be specified individually. This can take into account point flow increases caused by tributaries or lateral flows.

27.1.6 Variation of Manning's n with flow or hydraulic radius

One of the problems with WSP modeling at low flows is that there can be significant changes in the value of Manning's n. The way in which N changes with flow is calculated from pairs of stage and discharge measurements automatically.

If pairs of stage-discharge measurements are available at every cross-section, n can be varied at different rates between every pair of cross-sections. The coefficient used is the average of the values for the upstream and downstream cross-section. If pairs of gaugings are available only for the downstream cross-section, the variation at this cross-section is used for the whole reach.

27.2 Hydraulic losses

The theoretical base of uniform flow hydraulics and the empirical process of fitting or estimating values of n and loss coefficients is one of energy conservation. The theory is described in various hydraulic texts such as Henderson's "Open Channel Flow" and Ven Te Chow's "Open Channel Hydraulics" and is not repeated in detail here. IFG Group's Instream information paper No. 5 gives many practical hints on techniques used.

27.2.1 Velocity head

Between any two sections, there is a difference in water level and velocity head (v^2/2g). The total hydraulic losses - friction (Manning's n), bend, expansion and contraction - must equal the difference in level plus change in velocity head.

27.2.2 Friction loss

The friction loss is computed from the arithmetic average of the hydraulic properties of the upstream and downstream section.

27.2.3 Manning’s n

Values of Manning's n should not alter erratically through the reach. Usually values tend to be between 0.020 and 0.15 and to vary gradually through the reach with higher values in riffles and lower values in pools or runs.

If the head difference (water level + velocity) between the sections is negative, a value of N cannot be calculated. Such situations should not be possible hydraulically if cross-section locations were placed according to the criteria a set out earlier. The inability to calculate a value for N suggests an error in the measured water levels or poorly located cross-sections.

If a value for N cannot be calculated, the upstream water level may be underestimated or downstream water level overestimated. Either can be adjusted to effectively raise or lower a cross-section. Normally this adjustment should be within the range of measured left, right and midstream water levels.

28 Calculating Manning's n and loss coefficients

This describes the calculation of Manning's N for cross-sections and should not be confused with the values of manning's at points across the cross-section, as used in IFG4 emulation.

Values of Manning's n are calculated between pairs of cross-sections using:

- survey flow
- elevation difference
- section geometry

With good survey data, the calculated values of Manning's n are all positive (meaning that energy is lost as the river flows downhill) and within a consistent range (from about 0.02 in pools to 0.15 in riffles).

This calculation is a stringent check on the water level data, because a small error in level will negative values of n (shown as ***** in the output) usually accompanied by a correspondingly high value of n at the adjacent section. If satisfactory values are displayed, no further adjustment of hydraulic parameters is required.

28.1 Friction loss

Friction losses (Manning's n) are calculated between cross-sections, where friction loss is an average between two sections.

28.2 Adjustment of level

Occasionally the calculated value between 2 sections may be negative or unreasonably high. Adjustments to water levels and loss coefficients can be made so that n is positive and varies smoothly through the reach.

Field measurements of water level can be inaccurate and at times, it is appropriate to adjust cross-section elevations to obtain reasonable values of n. Adjustments of less than 1 mm will often achieve this, especially through pools.

Hydraulic loss coefficients for bends, contractions and expansions can also be estimated, but these are probably best used cautiously.

28.3 Water surface profile calculation method

The energy loss between two cross-sections is calculated from the average geometrical properties (conveyance) of the sections. This average can be calculated by two methods:

1. arithmetic mean
2. arithmetic mean when the friction slope is increasing and the harmonic mean when the slope is decreasing upstream

The latter method is the default and helps avoid some of the problems that can occur when calculating a convex profile. The method can be selected in the Options menu.

Interpolation of extra cross-sections is another way improving the accuracy of profiles over where slopes are changing rapidly. When interpolating between cross-sections, the hydraulic characteristics of intermediate cross-sections are calculated by linear interpolation between the sections upstream and downstream.

The friction slope is calculated by the Manning equation.

The roughness coefficient (Manning's n) can be varied with either flow or hydraulic radius.

The coefficient is assumed to vary logarithmically with either flow or hydraulic radius, according to:

$n = n_{calibration} * (Q/Q_{calibration})$ ^ beta

where q is the modeled flow, $Q_{calibration}$ the survey flow, and $n_{calibration}$ the value of roughness at the survey flow.

A value of 0 for beta is equivalent to not varying roughness.

The adjustment for the variation with hydraulic radius is of a similar form.

28.3.1 Cross-section beta values

Values of beta are shown for each cross-section in the ratings, Edit/select menu and in Fit roughness menu. Values can be altered if required.

The average of the beta values for upstream and downstream cross-sections is used to adjust the roughness between cross-sections and calculate friction slopes.

28.3.2 Reach beta values

If the water surface profile has been measured at more than the survey flow, and values are entered as gaugings, roughness values are calculated between each pair of cross-sections for each flow.

Logarithmic relationships are fitted to the roughness values and either flow or hydraulic radius to give reach beta values.

These values usually give the most accurate predictions of water surface profile.

29 Running command files (File/Load commands...)

Command files are ASCII text files that can be used to process a large number of files at one time.

A command file is selected using the Load commands item of the main Files menu. The command file has a suffix CMD and contains text listing the file name of the reach (the RHB file name), the flows to be evaluated, and whether the reach is to be merged with the previous reach. Reaches can be merged so that the result is an average over a number of reaches.

The CMD file can be a simple list of file names or if can specify the filename and a range of flows to process.

The simple list is:

filename1
filename2
filename3
filename4

where filename can be the full filename with path and extension, or the name of the rhbx file without the extension.

If the path is not specified, the files must be in the current directory of the directory containing the CMD file.

Flows can be specified as a range of flows, i.e. a minimum, maximum and interval or as a list of flows.

The format is:

```
filename1  flows 1.1   2.2   3.3   5.6   end
filename2  flows 1.1   2.2   3.3   5.6   end   merge
filename3  flows 1.1   2.2   3.3   5.6   end
filename4  flows 1.1   2.2   3.3   5.6   end
```

In the above example, files 1 and 2 are merged (only the first letter is necessary) and files 3 and 4 are processed separately.

All files are evaluated at flows of 1.1 2.2 3.3 and 5.6. If the word range is substituted for flows then the next 3 values are the flow minimum, maximum and flow interval.

The buttons on the graphic display, allow the results for each reach, or set of reaches if merged, to be displayed.

30 Printing and copying

Window contents can be printed by clicking on the print icon or selecting the print menu under File. This will display a dialog box showing a preview of the printed page. Text or graphic images can be printed to a file rather than directly to the printer if required.

30.1 Graphic images

Images can be sized and moved before printing by mouse. The dimensions of the graph can also be specified directly, either by setting the overall dimensions of the graph or by setting the axes dimensions in order to get a scalable graph (e.g. 1:100).

All graphs have a set of options  that allow graphs to be displayed in different ways.

Typical options allow alteration to:

- graph title
- Axes minimum and maximum values
- number of tick marks and decimal places for axes values
- the above values to be fixed for the window
- display of ticks, measurement points and grid
- Water level in terms of depth or elevation
- Display SZF on plot
- Color and background shading or fill (for printing or copying)

30.2 Copying graphs

Graphs can be copied to the clipboard for pasting into other programs. With some programs, it is necessary to paste graphs using the Paste Special and the Enhanced Metafile option .

Graphs can also be saved as windows metafiles or bitmaps using the Save As menu under the File menu.

30.3 Text fonts

Text fonts can be altered in Files>>Preferences>>Text font. If text is wider than the page then the page can be set to landscape or the font can be made smaller.

30.4 Copying text

Text windows with tables cannot be edited, but can be copied to the clipboard.

Graphs, text and tables can be copied to the clipboard either by clicking the copy icon  or selecting copy in the Edit/Display menu or by using the keyboard shortcut Ctrl C.

When text is pasted into a document tables can be reformatted using the Table AutoFormat function.

Plain text windows displayed when importing data can be edited and saved. This allows modifications to be made to HAB files that are imported. After making any modification to a hab file the file should be imported again.

Tables will paste as tables into WORD or as columns in EXCEL.

If Paste Special is used, text can be pasted as unformatted text, where tables are tab-delimited text.

31 Glossary

SEFA term	PHABSIM term	Description
Armour	Armor	The surface material left by the process of continually winnowing away smaller substrate materials and leaving a veneer of larger ones.
Attribute		A measure of a characteristic (e.g., substrate composition or index, cover) at a measurement point on a cross-section.
Backwater	Backwater	The water surface created in an upstream direction as a result of the damming effect of a vertical or horizontal channel constriction which impedes the free flow of water.
Base flow		This flow is used in a flow fluctuation analysis. It is the flow about which (or from which) flows fluctuate. The analysis compares the habitat under fluctuating flows with the habitat at the base flow.
Base line		Line joining zero points of cross-sections
Bed level		The level (elevation) of the ground
Bed profile		The measurements of bed elevation and offset (distance across the cross-section) that make up the cross-section
Best SZF rating		The rating curve using a SZF that results in the least deviation from the calibration gaugings. This SZF will always be greater than the minimum bed level.
Calibration gaugings		Measurements of stage and discharge at a cross-section that are used for the development of stage/discharge curves
Composite suitability (CSI)	Composite suitability	A weighting factor depicting habitat quality, derived by mathematically aggregating several univariate suitability functions (e.g., by multiplication of univariate suitabilities).
Constant		The multiplier in the rating equations. This is the constant term in a linear regression of logarithms.
Cover	Cover	Structural features (e.g., boulders, logjams) or hydraulic characteristics (e.g., turbulence, depth) that provide shelter from currents, energetically efficient feeding stations, and/or visual isolation from competitors or predators.
Critical flow	Critical flow	The flow condition that occurs at a location in the river (e.g. a weir) where the downstream water level has no effect on the water levels upstream.
Critical rating		The rating curve derived so that the flow in the cross-section is critical
Cross-section weight		A multiplier that weights each cross-section. In a representative reach the weights are usually based on the distance between cross-sections and in a habitat mapped reach they are based on the proportions of the habitat types in the reach.
Datum	Datum	The elevation of a point used as a reference in surveying, mapping, or geology. In SEFA, the datum can be a known or assumed elevation.
Depth	Depth	For a point, the depth is the difference between the water level and bed elevations. For a cross-section, it is the width-weighted average depth and is equal to the cross-section area divided by the wetted width. For a reach, it is the cross-section average depths weighted by the cross-section weights.
Discharge	Discharge	The rate of stream flow or the volume of water flowing at a location within a specified time interval, expressed as cubic meters per second (m3/s) or cubic feet per second (cfs).
Distance	Distance	Distance of cross-section along the river. Identification number for cross-section where the location of the cross-sections is not necessary for calculation, as when a reach is weighted by habitat mapping.
Duration analysis	Duration analysis	An analysis the gives the percentage of time a class (magnitude) of events occurs.
Energy slope	Energy slope	The difference in total energy (potential plus kinetic) of a fluid between two points, divided by the linear distance between the two points.
Exceedance	Exceedance	The probability or % of time that an event in a time series will be equaled or exceeded in magnitude by other events in the same series.
Exponent	Beta	The power term (exponent) in the SZF, Best SZF and WSP ratings. This is the multiplier in the linear equation of the logarithms.
Flushing flow	Flushing flow	A stream discharge with sufficient power to remove silt and sand from a gravel/cobble substrate but not enough power to remove gravels.
Froude number	Froude number	An index of hydraulic turbulence defined as: *Fr*= V/gD where *V*is velocity, g is the acceleration of gravity, and *D* is depth. If *Fr* is less than unity, flow is sub critical and described as tranquil or streaming. If *Fr* is

		greater than unity, flow is supercritical and described as torrential or shooting.
Gauging	Gauging	A measurement of flow in a cross-section
Geometric mean	Geometric mean	An alternative algorithm for calculating the composite suitability index from three univariate suitability functions by the equation:
Habitat	Habitat	The physical and biological surroundings in which an organism or biological population usually lives, grows, and reproduces.
Habitat suitability criteria or curves (HSC)	Habitat suitability criteria or curves	Habitat suitability curves (or criteria) that define suitability index of between 0 and 1 for hydraulic habitat variables or other variables. Graphical or numerical tables that define the relative utility of increments or classes of habitat variables to a life stage of a species
Height above SZF		The stage less the SZF
Hydraulic control	Hydraulic control	A horizontal or vertical constriction in the channel, such as the crest of a riffle, that creates a backwater effect (i.e. it influences upstream water levels)
Hydraulic habitat	Physical habitat	The habitat created by water depth, velocity, and characteristics (attributes) of a measurement point in a river.
Hydraulic radius	Hydraulic radius	The cross-sectional area of a cross-section divided by the wetted perimeter.
Hydraulic rating	ManSQ	Rating curve derived from a hydraulic equation (Manning's) and a relationship between roughness and flow.
Hydrograph	Hydrograph	- graph showing the variation in discharge over time.
Life stage	Life stage	An arbitrary age classification of an organism into categories related to body morphology and reproductive potential (e.g., spawning, larvae, fry, juvenile, adult).
Lowest bank	Lowest bank	The lesser of the highest points on the left and right banks of a cross-section
Manning's n	Manning's n	An empirical calibration parameter used in the Manning equation to represent roughness, or resistance to flow, as a function of the size and irregularity of streambed materials relative to depth of stream flow (e.g., large particles in shallow water are "rougher" than small particles in deep water).
Mesohabitat	Mesohabitat	A discrete area of stream exhibiting relatively similar characteristics usually assessed on the basis of water surface characteristics (e.g., pool, run, riffle).
Minimum bed level	Minimum bed level	The lowest point on a cross-section
Offset	Station	Offset (distance) of measurement point from baseline (zero point or head pin) of cross-section
Point	Station	Point or station where the measurement (of offset, depth, velocity, attributes) is carried out
Rating curve	Rating curve	Relationship between the stage and flow at a cross-section
Reach	Reach	Area of the river where the survey is made.
Reference reach		This is the first reach specified when more than 1 reach is analyzed in a multiple or combined reach analysis. For example, if 2 reaches are analyzed together and there is a flow difference (e.g. tributary flow) between the 2, the flows in the results refer to the first reach entered - the reference reach.
Representative reach	Representative reach (WSP)	A length of stream used to represent the characteristics of a segment, assumed to contain all of the habitat types of the segment in the same proportions as the segment. The cross-sections are usually topographically related (distances specified) with a common datum.
Habitat mapping reach	Representative reach (IFG4)	A length of stream used to represent the characteristics of a segment, assumed to contain all of the habitat types of the segment in the same proportions as the segment. The proportion of the reach represented by each cross-section is specified and cross-sections need not be to a common datum.
Riparian	Riparian	Pertaining to the banks of a natural watercourse, that is, adjacency to the active channel.
Section or cross-section	Cross-section or transect	Surveyed cross-section of the river channel (including measurements in and above water level)
Segment	Segment	A relatively long (e.g., hundreds of channel widths) section of a river with consistent morphology (e.g. similar geology, bank composition, flow and slope).
Selectivity	Selectivity	The ratio of the density of animals in a particular resource (i.e. habitat

		category or interval) to the average density in the river
Stage	Stage	Water level (elevation) in terms of a datum level. The distance of the water surface in a river above or below a known reference point or datum.
Stage of zero flow (SZF)	Stage of zero flow (SZF)	The water surface elevation at a cross section when the discharge is zero. The water level (stage) when the flow falls to zero. When this is used in the derivation of rating curves it is the effective stage at zero, which will be at or greater than the actual SZF.
Stage/discharge curve	Stage/discharge curve	Relationship between the stage and flow at a cross-section
Standard setting	Standard setting	A policy of using a fixed rule or equation to determine minimum instream flow for a stream, usually based on a hydrological statistic rather than on bi logical criteria.
Substrate	Substrate	The surface material of the stream bed, for example, sand, gravel, cobble, boulders.
Suitability	Suitability	A generic term used to indicate the relative quality of a range of environmental conditions for a species.
Survey flow (discharge)	Best estimate of flow	Best estimate of the flow (discharge) at the time the cross-section date was collected
Survey stage		Stage at which the cross-section data were collected
SZF rating	Log-log rating	Stage discharge relationship developed by least squares fit to the logarithms of flow and the height above SZF It has the form: flow = constant*(water level - SZF)^exponent
Thalweg	Thalweg	-A longitudinal profile of the lowest elevations of a sequential series of cross sections.
Transect		Line across river containing multiple channels (braids)
VDF (or Manning's n)	Manning N at cross-section points	The velocity distribution factor calculates the velocities across a cross-section. It is the ratio of the measured velocity to the velocity that would be predicted at a point by conveyance equations assuming uniform roughness.
Velocity	Velocity	For a point, the velocity is the measured or predicted mean column (average in the vertical) velocity. For a cross-section, it is the width-weighted average velocity and is not equal to the flow divide by the cross-section area (the latter is an area weighted velocity). For a reach, it is the cross-section average velocities weighted by the cross-section weights.
Velocity adjustment factor	Velocity adjustment factor	The ratio between the input discharge and the discharge initially calculated from the calibration VDFs or Manning Ns for the input discharge.
Water surface profile	Longitudinal profile	The longitudinal profile of water surface elevation along a river.
Wetted area	Wetted area	The area of the river that is under water
Wetted perimeter	Wetted perimeter	The total length of the bed profile that is under water
Wetted perimeter	Wetted perimeter	The length of the line of intersection of the channel wetted surface with a cross-sectional plane normal to the direction of flow.
Wetted width	Wetted width	The total width of a cross-section that is under water.
Width	Width	Wetted width
WSP	Step backwater	The calculation of water surface profile using the step-backwater method.
WSP rating	Log-log rating	Stage discharge relationship developed by least squares fit to the logarithms of flow and water levels predicted by WSP analysis less the SZF.