Special Report Number 80

FISH-FLOW INVESTIGATION

I. TWO-DIMENSIONAL MODELING FOR PREDICTING FISH BIOMASS IN WESTERN COLORADO

Gregory Stewart and Richard M. Anderson

II. IMPACTS OF STREAM FLOW ALTERATIONS ON THE NATIVE FISH ASSEMBLAGE AND THEIR HABITAT AVAILABILITY AS DETERMINED BY 2D MODELING AND THE USE OF FISH POPULATION DATA TO SUPPORT INSTREAM FLOW RECOMMENDATIONS FOR THE SECTIONS OF THE YAMPA, COLORADO, GUNNISON AND DOLORES RIVERS IN COLORADO

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May 2007

COLORADO DIVISION OF WILDLIFE
AQUATIC WILDLIFE RESEARCH

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FOREWORD

In our semi-arid state, water is a scarce resource with many competing demands placed on it by an ever-growing population. The amount of water that should be retained in streams and rivers for the benefit of fish is of concern to resource managers. In 1973, the State Legislature recognized the need to correlate the activities of mankind with some reasonable preservation of the natural environment. It vested the Colorado Water Conservation Board (CWCB) with the exclusive authority to appropriate and acquire water for instream flows to preserve or improve the natural environment to a reasonable degree. To learn more about the mandate and programs of the CWCB Stream and Lake Protection Section, visit their web site at http://CWCB.state.co.us.

In 1999 CWCB asked the Colorado Division of Wildlife (CDOW) to provide biologically justified instream flow recommendations for the Colorado and Yampa Rivers. In response to this request, the research study titled "Fish-Flow Investigations" was initiated by the CDOW Aquatic Research Group to evaluate two-dimensional (2D) flow models for use in determining preferred habitats of native fish in these rivers and subsequently to develop flow recommendations which would protect these unique species assemblages.

This Special Report is the final report from this research assignment and provides water and fishery managers with valuable information relating flows and flow patterns to native fish abundance in western Colorado rivers. It is divided into two separate parts. Part One describes the approach, methods and results using 2D modeling for relating flow and fish habitat availability. Part Two describes and summarizes the fish data collected at each sample site with the objective of relating flow to fish abundance using the hydrologic tools outlined in Part One. In addition, Part Two makes comparisons between sites and draws conclusions from the observed conditions.

We believe that the product of this report taken in whole provides a methodology which may be used by resource managers to recommend instream flows based on biologically validated models. The 2D modeling approach is another tool in the "tool box" of those responsible for protecting native fish communities in western Colorado rivers.

Mark S. Jones
Aquatic Research Leader

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EXECUTIVE SUMMARY

The quantity of water that should be retained in streams and rivers for the benefit of fish during periods of water scarcity is a question of considerable interest to river managers and biologists. The most common type of instream flow methodology utilizes empirically derived habitat suitability indices and flow models to predict how flows affect individual fish species and life-stages. Although these instream flow methodologies have existed since the 1970's, no single method has been widely accepted for use on large warm-water rivers because of their high species richness and generalized fish habitat use patterns.

In this report we present a methodology developed by the Colorado Division of Wildlife (CDOW) that is similar to the Instream Flow Incremental Methodology. The CDOW methodology utilizes two-dimensional (2D) flow models and meso-habitat fish community biomass estimates to evaluate the effects of flow alteration on Western Colorado rivers. Data collected from the Colorado and Yampa Rivers are used to develop habitat suitability criteria for bluehead and flannelmouth sucker (*Catostomus discobolus*, *C. latipinnis*) by comparing adult biomass in individual meso-habitat units with modeled depths and velocities.

Implicit in the development of habitat suitability criteria is the idea that the criteria have some predictive capability, though this is rarely tested. To test the predictive capability of the methodology, we use habitat suitability criteria developed from data collected between 1998 and 2001 to predict biomass on the Colorado and Yampa rivers from 2002 to 2004. Regression between measured biomass and biomass predicted from 2001 habitat suitability curves show strong agreement between measured and predicted biomass (r^2 = 0.90 and 0.74 for bluehead and flannelmouth sucker respectively). Curves developed for the Yampa and Colorado were found to have less predictive power when applied to the Gunnison River.

This study confirms our assessment that relationships between fish biomass and water depth and velocity determined with 2D models can be used to evaluate differential effects of flow alteration in Western Colorado rivers with similar geomorphology to the Yampa and Colorado, where native species compositions are present and where flow is the limiting factor.

INTRODUCTION

In Western Colorado, as in many regions in the world, increased demands for water have resulted in significant alteration of the hydrologic system. Apparent synchrony between native fish species declines and development of water resources has fueled concerns over the effects of flow alteration on river ecosystem function and integrity. To evaluate the effects of river discharge on fisheries and fish habitat, researchers have developed a number of methodologies that combine measurements or models of habitat as a function of flow with relationships between habitat and fisheries response. The most widely used of these is the Instream Flow Incremental Methodology (IFIM) (Reiser et al. 1989).

In IFIM, a physical habitat simulation model (PHABSIM) is used to quantify the effect of changing discharge on physical variables of interest, including depth, velocity, cover and substrate (Bovee et al. 1998). PHABSIM relies on a variety of one-dimensional (1D) step-backwater hydraulic models that calculate depth and average velocity at cross-sections over a range of flows (Tarbet and Hardy 1996). Modeled velocity is distributed across the channel based on velocity distributions measured in the field over a specified range of flows. The probability that an individual of a specific species and life-stage has been observed occupying some range of depth, velocity, substrate/cover provides the habitat suitability criteria. Weighted useable area (WUA), a measure of habitat area based on observations of habitat suitability, represents microhabitat availability for a target species (Stalnaker et al. 1995). Temporal variability is accounted for by integrating hydrologic time series and 'habitat versus discharge' relationships to generate a habitat time series (Hardy 1998).

IFIM has been criticized for both physical and biological reasons, including: 1) difficulties in establishing a relationship between WUA and population response, 2) the focus on single species and life stages, 3) the use of 1D flow models which, by definition, cannot accurately represent velocity distributions in rivers with significant lateral flow components and 4) a lack of studies that validate the methodology (Bovee 1996; Espegren 1998; Jowett 1997; Mathur et al., 1985; Scott and Shirvell 1987; Tharme 2003; Stewart et al. 2005).

Assessing the habitat requirements of fish in warm water rivers using PHABSIM is especially problematic (Rose and Hahn 1989; Nestler 1990). In warm water rivers, habitat suitability based on microhabitat observations may not be appropriate because of the high species richness and generalized habitat use patterns of fish (Bain and Boltz 1989; Bowen et al. 1998). Instead, a broader community level perspective that simultaneously considers multiple species is required for examining the relationship between flow and habitat because of the likelihood of differential species response to varying stream flows (Lobb and Orth 1991; Anderson 1998).

A number of authors have suggested that 2D flow models should offer significant improvement over 1D modeling in determining habitat metrics as a function of flow (Leclerc et al. 1995; Bovee 1996; Ghanem et al. 1996; Hardy 1998; Kondolf et al. 2000; Guay et al. 2000). One-dimensional flow models calculate downstream changes in water-surface elevation and velocity between individual channel cross-sections while 2D flow models calculate downstream and lateral components of flow [three-dimensional models (3D) include vertical velocities]. Instream flow assessments based on 1D modeling can account for temporal variability in discharge, but are poorly suited to the analysis of spatial metrics. Spatially explicit flow models (2D & 3D) are necessary to describe the spatial and temporal heterogeneity in a river system, not only to model the physical features of the habitat, but also to permit a better understanding of the processes that may be limiting fish existence, including habitat heterogeneity/diversity (Bovee 1996; Ghanem et al. 1996). Because 2D model results are spatially explicit, they are ideally suited for computation of landscape ecology metrics across a variety of spatial scales, such as examination of habitat utilization and variability at the scale of a fish community (Bovee, 1996; Hardy 1998).

Biological data are most efficiently collected at the meso-habitat scale and 2D hydraulic models most accurately simulate meso-scale flow patterns (Crowder and Diplas 2000; Parasiewicz 2001). Suitability criteria collected at the meso-habitat scale are also more likely to be transferable to sympatric species or guilds (Parasiewicz 2001). As such, fish data for this study are collected and analyzed at the meso-habitat unit scale, which consist of a single habitat type (e.g. pool, riffle, run) 1-10 channel widths in length. Actual biomass in each meso-habitat is determined through estimates of community biomass distributed among meso-habitats.

STUDY AREAS

The three rivers examined in this study are all part of the greater Colorado River system in Western Colorado. Discharge in each river is currently modified from the historic flow regime, though the magnitude and timing of flow change is different in each case. Fish data collected on the Dolores River was not incorporated into this study because species composition was significantly different than that found at the other study sites (see Anderson and Stewart 2006a).

Yampa River

The Yampa River flows through the northwest portion of Colorado from its headwaters near Steamboat Springs to its confluence with the Green River. The Yampa is unusual in Colorado because it contains no mainstem dams. Summer base flows are reduced by irrigation withdrawals, yet the spring runoff flow is largely unmodified. According to Colorado River Decision Support System (CRDSS) models, Yampa River discharges in August and September average only 70 percent of native late summer low flows (Modde et al., 1999). Three study sites were located on the Yampa River: Duffy (40.430°N, 107.857°W, WGS84/NAD83), Sevens (40.513°N, 108.299°W), and Lily Park (40.455°N, 108.412°W) (Figure I-1). Duffy is located at RM 109 and was 7.2 km in length; Sevens is located at RM 64 and is 2.9 km in length; and Lily Park is located at RM 52 and is 3.1 km in length. Each site contains slightly different fish and habitat characteristics, but all are geomorphically similar with riffle-run morphologies (slopes 0.06 percent, 0.05 percent, and 0.20 percent, respectively). Duffy contains a large population of non-native fish, including white suckers (*Catostomus commersoni*), smallmouth bass (*Micropterus dolomieu*) and sucker hybrids, whereas Sevens and Lily Park sites a re predominantly native fish species (Anderson 2005).

Colorado River

The Colorado River originates in the Rocky Mountains, flows westward through central Colorado and leaves the state just west of Grand Junction, CO. The upper Colorado contains a large number of upstream water projects that store water for out-of-basin delivery. As a result, peak flows at the Cameo gage located just upstream of Grand Junction average 60 percent of pre-impoundment flows. While peak flows during spring runoff are significantly reduced, downstream demands for irrigation water result in historically high summer base flows in the 15-mile reach of the Colorado River. The two Colorado River sites, Clifton (39.063°N, 108.438°W) and Corn Lake (39.055°N, 108.466°W), are located adjacent to one another in the 15-mile reach, and together cover 8.1 km of channel length (Figure I-2). Both sites have riffle-run morphologies (slopes 0.20 percent and 0.16 percent, respectively) and contain large native fish species populations. The greatest difference in the sites is that Clifton is wider with an anastamosing channel planform, whereas Corn Lake is laterally constrained.

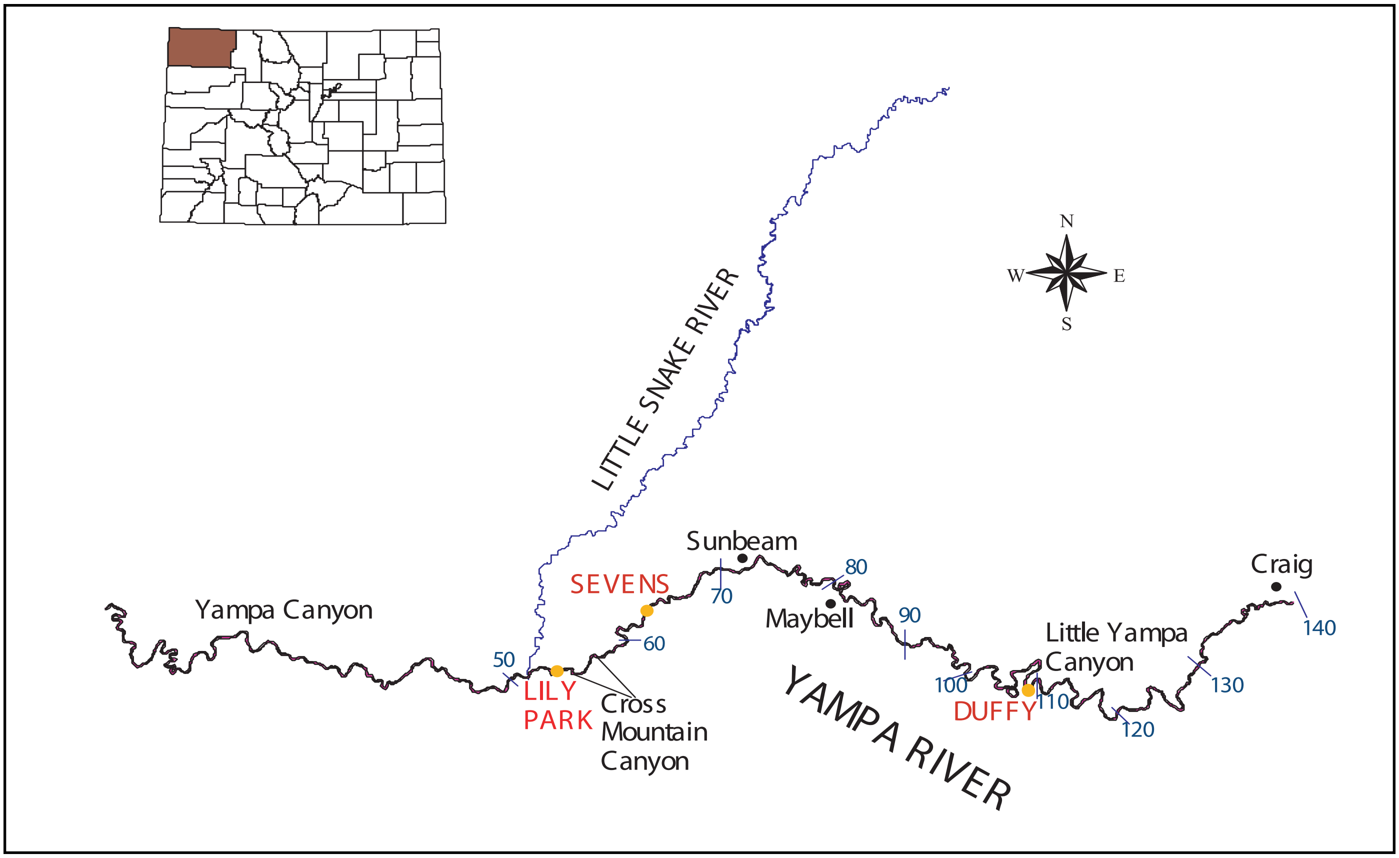


FIGURE I-1. Yampa River study site locations: Lily Park (RM 53), Sevens (RM 64) and Duffy (RM 109).

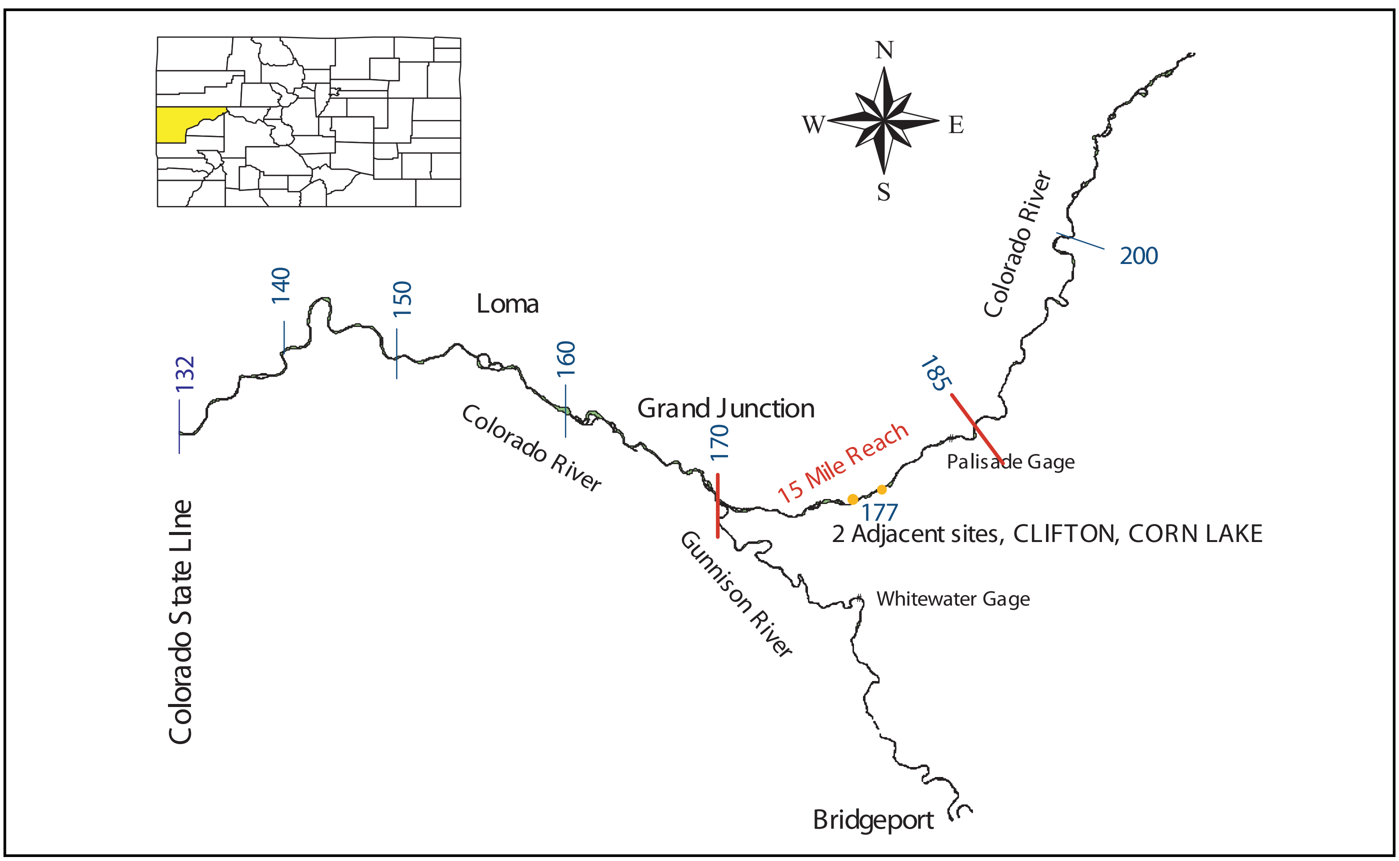


FIGURE I-2. Colorado River study site locations in the 15-Mile Reach: Corn Lake and Clifton (RM 175 -180).

Gunnison River

The Gunnison River is the largest tributary to the upper Colorado River, with its confluence located just downstream of the 15-mile reach of the Colorado River near Grand Junction, CO (Figure I-2). The Gunnison is heavily affected by the Aspinall water project (Blue Mesa, Morrow Point and Crystal reservoirs), which was completed between 1966 and 1976. Peak flows during spring runoff are less than half their historic pre-project levels, while minimum flows are almost twice as high. The two Gunnison River sites are Delta (38.750°N, 108.104°W), which is 3.9 km long, and Escalante (38.760°N, 108.279°W), which is 4.4 km long (Figure I-3). Both sites have riffle-run morphologies, but the Delta site has a slightly higher channel gradient than the Escalante site (0.16 percent and 0.09 percent respectively). The base flow hydrograph of the Gunnison River is substantially higher than the Yampa and Colorado Rivers (Anderson and Stewart 2006a).

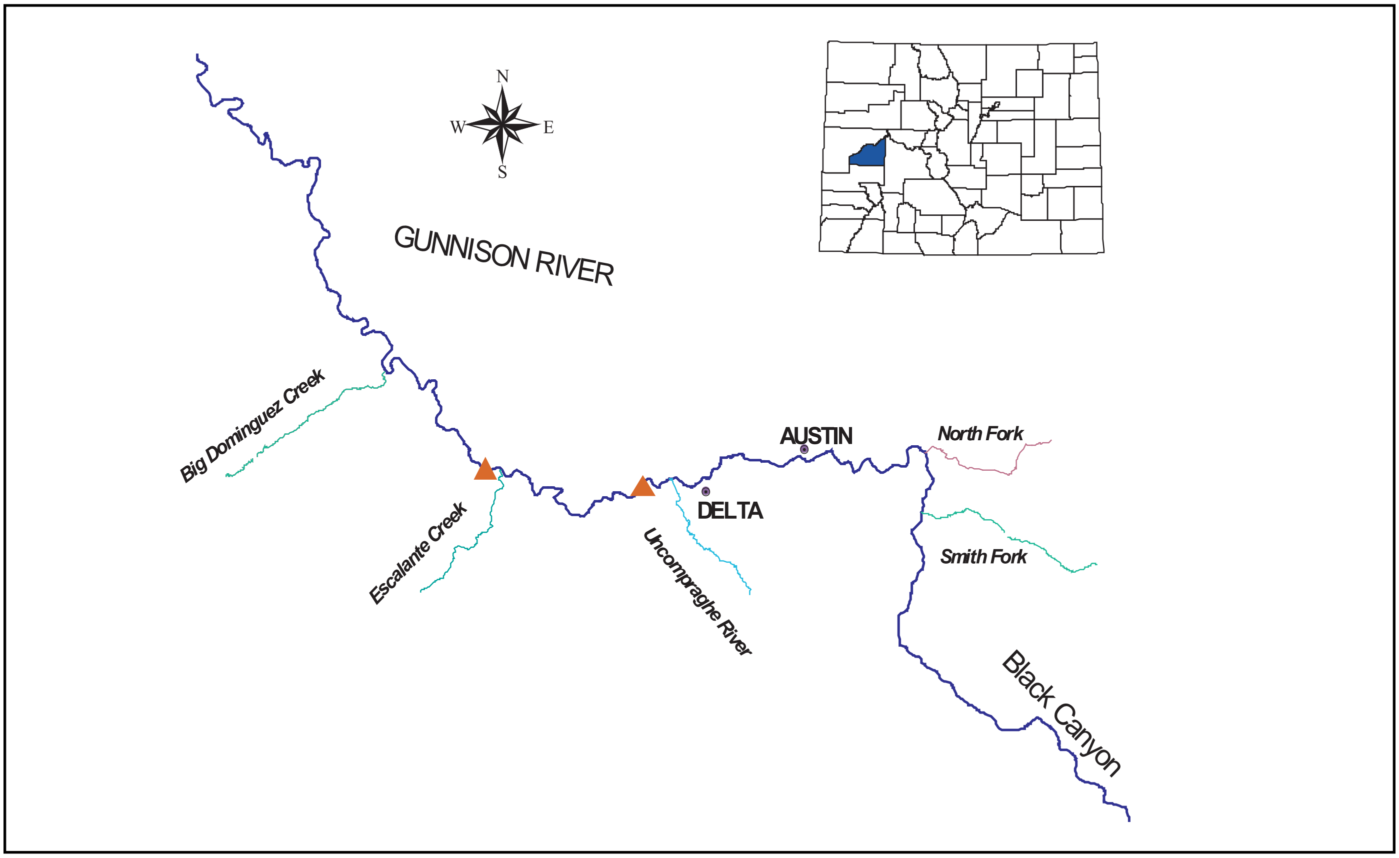


FIGURE I-3. Gunnison River study site locations: Escalante (RM 43) and Delta (RM 56)

METHODS

The methods employed for this study are generally the same as those described by Stewart et al. (2005). Fish density estimates differ slightly from those reported in Anderson and Stewart (2003) and Stewart et al. (2005) because they incorporate the Chapman (1954) adjustment factor formula with the Darroch multiple mark methods (Everhart and Youngs, 1981). Creation of revised habitat suitability criteria, as discussed below, also resulted in a small change in which habitat suitability became binomial with habitat and non-habitat categories.

Fish Sampling

Fish were sampled by electro-shocking and netting from a 4.9 m raft rigged with a Smith-Root electro-fisher, 5000-watt generator, and anode array mounted on a forward boom. The boat was maneuvered with oars and/or battery-powered 18.1 kg thrust trolling motor. Two netters caught fish and all were measured to the nearest millimeter. Only fish over 150 mm were used for mark-and-recapture population estimates. Density estimates were made for each year at each of the study sites on the Yampa, Colorado and Gunnison Rivers.

The Darroch multiple mark method (Everhart and Youngs 1981) with the Chapman (1954) formula was used to make population estimates with 95 percent confidence intervals. A total fish estimate was made for each site and for each species. Recapture rates varied between species and size-groups. In general, larger suckers had the highest recapture probabilities. Channel catfish (*Ictalurus punctatus)*, bass (*Micropterus salmoides* and *Micropterus dolomieu*), northern pike (*Esox lucius*) and common carp (*Cyprinus carpio*) had appreciably lower recapture probabilities. The total fish estimate represented a blend of recapture probabilities, but produced reliable comparisons of total fish abundance between years when species and size composition was consistent. For species with zero or one recapture, abundance was estimated by dividing number collected by the recapture probability of the lower group.

Within sites, electro-fishing was performed at the meso-habitat scale (individual runs, riffles, pools approximately 1-10 channel widths in length). These sub-reach sampling units had the same start and end locations between passes and years and were digitized into a GIS format from aerial photographs of the study sites. Species density and biomass was calculated by multiplying the percentage of a given species caught in each sub-unit by the total-reach estimate, determined from mark-and-recapture probabilities, for that species and year. Biomass was estimated for flannelmouth sucker, bluehead sucker and roundtail chub (*Gila robusta*) over 20 cm in length. Individuals smaller than 20 cm in length were not included in any biomass estimates.

Channel Mapping

A Javad Oddessy L1/L2 Real Time Kinematic (RTK) Gobal Positioning System (GPS) was mounted on the side of a boat directly over an ODOM Hydrographic Systems, Hydrotrac - Single Frequency, Portable Survey Sounder. The Javad RTK GPS was optionally equipped with advanced multi-path reduction and the ability to receive both GPS and Glonass satellites. Published vertical accuracy for the GPS system is 15 mm +/- 1.5 mm per kilometer of distance between the base station and rover GPS units. Repeat field measurement of a single monument located one km from the base-station gave a vertical standard deviation of two mm. The ODOM Hydrotrac Sounder operated at 200 kHZ and output readings at a rate of 10 Hz with a published accuracy of one cm +/- 0.1 percent of depth.

The GPS and Sounder output data received at different rates (one Hz and 10 Hz, respectively), so a Comlog program tagged incoming data with the time to the nearest millisecond. An XYZ dataset was created by linearly interpolating the depth at each GPS reading. To ensure that the entire channel was mapped without large gaps in coverage, GPS data were also logged using ArcView Tracking Analyst to create real-time maps showing locations where bathymetric data had been collected. Mapping was done through a combination of longitudinal and cross-sectional surveys.

Two-dimensional models require calibration, so water-surface elevations and extents were mapped using the RTK GPS mounted on a range pole. Additionally, water depth and velocity were measured with a three MHZ Sontek River Surveyor Acoustic Doppler Profiler (ADP) at some sites for use in model calibration/validation. Velocity measurements were depth-averaged in 15 cm increments over channel depth and measurements were recorded over a 30-second time-period by holding the boat steady at one place in the river. RTK GPS was used to reject readings in which the boat moved over three meters during the 30-second period.

Hydraulic Modeling

In the first two years of the project, hydraulic modeling was performed using RMA2 (version 4.3), a 2D hydraulic model distributed with the Surface Water Modeling System (SMS) software package from EMSI [www.ems-i.com]. RMA2 is a depth-averaged finite element hydrodynamic model created for the Corps of Engineers in 1973 (King 1997). RMA2 computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in 2D flow fields using a finite element solution of the Reynolds form of the Navier Stokes equations for turbulent flows. Two-dimensional models are applicable to problems in which vertical accelerations are negligible and velocity vectors generally point in the same direction over the entire depth of the water column.

The development of a RMA2 simulation starts with creating a finite element mesh. SMS allows the user to import shapefiles or aerial photographs for use in creating the mesh boundaries. Accurate identification of mesh boundaries are important where wetting and drying is incorporated through elemental elimination, which has the potential to cause model divergence. In addition, elemental elimination of either an inflow or outflow boundary will cause the model to stop. Because the purpose of this project was to model a range of flows, including very small discharges, it became necessary to create artificial rectangular channels at both ends of the modeled reaches. These artificial channels allow the model to have stable boundary conditions that never go dry. The Hydrologic Engineering Centers River Analysis System (HEC-RAS) was used to develop stage discharge relationships for the artificial rectangular channels. HEC-RAS output was also calibrated against known water surface elevations to estimate a Manning’s n roughness coefficient for the channel.

Following the delineation of mesh boundaries, a finite element mesh can be automatically populated with triangular and/or rectangular elements. Mesh elements must then be assigned boundary conditions including bed elevations, roughness coefficients and local eddy viscosity. RMA2 requires that discharge and water surface elevation be applied to the upstream and downstream boundaries and simulations can be run as either steady state or dynamic. Dynamic simulations are best used for modeling tidal conditions or looking at regulated rivers with large ramping rates where kinematic wave approximations are important. In most river settings where the river changes gradually and depth and velocity are not significantly affected by the river stage at a previous time, it is easier and more appropriate to model steady state conditions (King 1997).

RMA2 simulations are started with a flat global water surface elevation where water surface at the downstream boundary is specified higher than the highest node in the model. Two-dimensional velocities are considered to be zero and the depth at each node is calculated as the difference between initial water surface and the bed elevations from the mesh geometry. Using revision (REV) cards in the boundary condition file, the downstream boundary condition is lowered incrementally to the known downstream water surface elevation for a given discharge. The stepping down process in RMA2 can be very difficult and time consuming, especially when the mesh boundaries may not coincide with the water surface elevation of interest, or in rivers with a high gradient. Because RMA2 uses the last solution for initial guesses for water surface slope, depth and velocity, small increments are required to avoid model divergence. Once the known water surface elevation has been reached using the REV cards, a solution file can be exported to the SMS interface. The solution file contains the depth, velocity and water surface elevation for each node in the mesh. SMS allows the user to create contour maps of those attributes as well as maps containing velocity vectors showing direction of flow. The data contained in the solution file can be further exported to a tab-delimited file for use in other programs.

Although modeling with RMA2 presented only minor difficulties (Stewart 2000), Duffy, Sevens and Corn Lake were the only sites that were modeled with RMA2. When the project was expanded to other sites, hydraulic modeling was contracted to Dr. Craig Addley at Utah State University (USU). The USU modelers used methods similar to those described above, but used a 2D hydraulic model code developed by Jonathan Nelson of the USGS instead of RMA2. The technical description and underlying equations of the model used by USU can be found in Nelson et al. (1995), Nelson (1996), Thompson et al. (1998), McLean et al. (1999) and Topping et al. (2000). Methods and results of USU and RMA2 modeling are comparable and two sites were re-modeled by USU (Sevens and Corn Lake) to expand the range of flows over which the modeling was performed. Both RMA2 and USU models used finite element meshes with rectangular elements (RMA2 meshes had a limited number of triangular elements) and maximum nodal distances of three meters laterally and five meters longitudinally. In smaller channels, smaller elements were used. Hydraulic simulations were performed over a range of discharges at each site.

Meso-Habitat Suitability

Suitability criteria for individual species were created from 2D modeling and meso-habitat fish biomass estimated for 1998 through 2001 from Clifton, Corn Lake, Lily Park and Sevens. Duffy was excluded from the suitability analysis because native species represented less than 16 percent of the fish caught. Using the 2D modeling data, mean depth and velocity were determined for each meso-habitat unit as a function of discharge. Depth, velocity and meso-habitat biomass at known discharges were subsequently imported into Sigma Plot and smoothed into a single rectangular matrix using a running median function over the nearest 10 percent of the data. The running median function provided estimates of reasonable biomass values over a wide range of depths and velocities, but it was not able to predict biomass beyond the range of observed depth, velocity and predicted biomass where none was observed (e.g., depths close to zero). The matrices were manually edited to eliminate biomass where no biomass was observed and to extend the range of depths and velocities by mirroring data beyond the observed range. Data were lumped into four general habitat suitability categories (unusable, unsuitable, marginal and optimal) representing approximately zero percent, 15 percent, 25 percent and 60 percent of the sampled biomass, respectively (Stewart et. al. 2005).

Following biological data collection on the Gunnison, new revised habitat suitability matrices were developed. During development of these habitat suitability criteria, it was noted that the inclusion of unsuitable (15 percent) and marginal (25 percent) did not improve the relationship between observed and predicted biomass. As a result, the final revised habitat suitability matrix was binomial with only habitat (60 percent) and non-habitat (40 percent) designations.

RESULTS

Hydraulic Model Validation

In this study, USU 2D hydraulic models were calibrated against measured water-surface elevations whereas RMA2 models were calibrated with measured depth and velocity data at the highest modeled discharge. Model results were later evaluated for their ability to reproduce hydraulic conditions by comparing model results against field measurements of depth and velocity. RMA2 was calibrated at 600 cfs and 1800 cfs and was validated at 300 cfs and 1200 cfs for Duffy and Corn Lake, respectively. ADP depth and velocity data were collected at only four sites: Duffy (RMA2), Clifton (USU), Corn Lake (RMA2 & USU) and Delta (USU), so only five 2D simulations were validated.

With the exception of Delta, each simulation data appeared to reproduce patterns in the observed data, although depths tended to be slightly over-predicted or under-measured (Table I-1, Figure I-4). The modeling for Duffy, Clifton and Corn Lake explained 76 percent of the measured depth and velocity on average with both USU (n=2) and RMA2 (n=2) performing equally well. The flow model for Delta had poor explanatory power, with measured depth and velocity explaining only 37 percent and 40 percent of modeled depth and velocity, respectively (Figure I-5).

Determination of Habitat Suitability

Habitat suitability indices were developed using fish and 2D modeling data from Clifton, Corn Lake, Sevens and Lily Park collected between 1998 and 2001 for bluehead and flannelmouth sucker (Figures I-6 and I-7). Fish data collected at Duffy Tunnel was not used in the development of the habitat suitability criteria because the site did not contain significant numbers of adult native fish (Anderson and Stewart 2003). Generalized habitat suitability criteria were then used to calculate total predicted biomass for each site using modeled depth and velocity. A comparison between observed and predicted biomass shows that this generalized habitat suitability model reasonably predicts bluehead sucker (r^2=0.88, n=11, Figure I-8). In 2000, summer low flows at Lily Park created pocket pools that allowed abnormally high numbers of flannelmouth sucker and channel catfish to be caught (Anderson and Stewart 2003). With the 2000 Lilly Park biomass included, the correlation between observed and predicted biomass is r^2=0.33 (n=11), but it increases to r^2=0.61 (n=10) when this outlying data point is removed (Figure I-9).

TABLE I-1. Relationship between observed and modeled depth and velocity. Slopes >1 represent over-prediction by the model while slopes <1 represent under-prediction.

			Depth		Velocity	
Site	Model	n	r^2	Slope	r^2	slope
Duffy	RMA2	40	0.98	1.00	0.57	0.52
Clifton	USU	60	0.73	1.00	0.74	1.06
Corn Lake	RMA2	23	0.68	0.74	0.91	1.12
Corn Lake	USU	26	0.65	0.74	0.81	0.96
Delta	USU	143	0.37	0.88	0.40	0.89

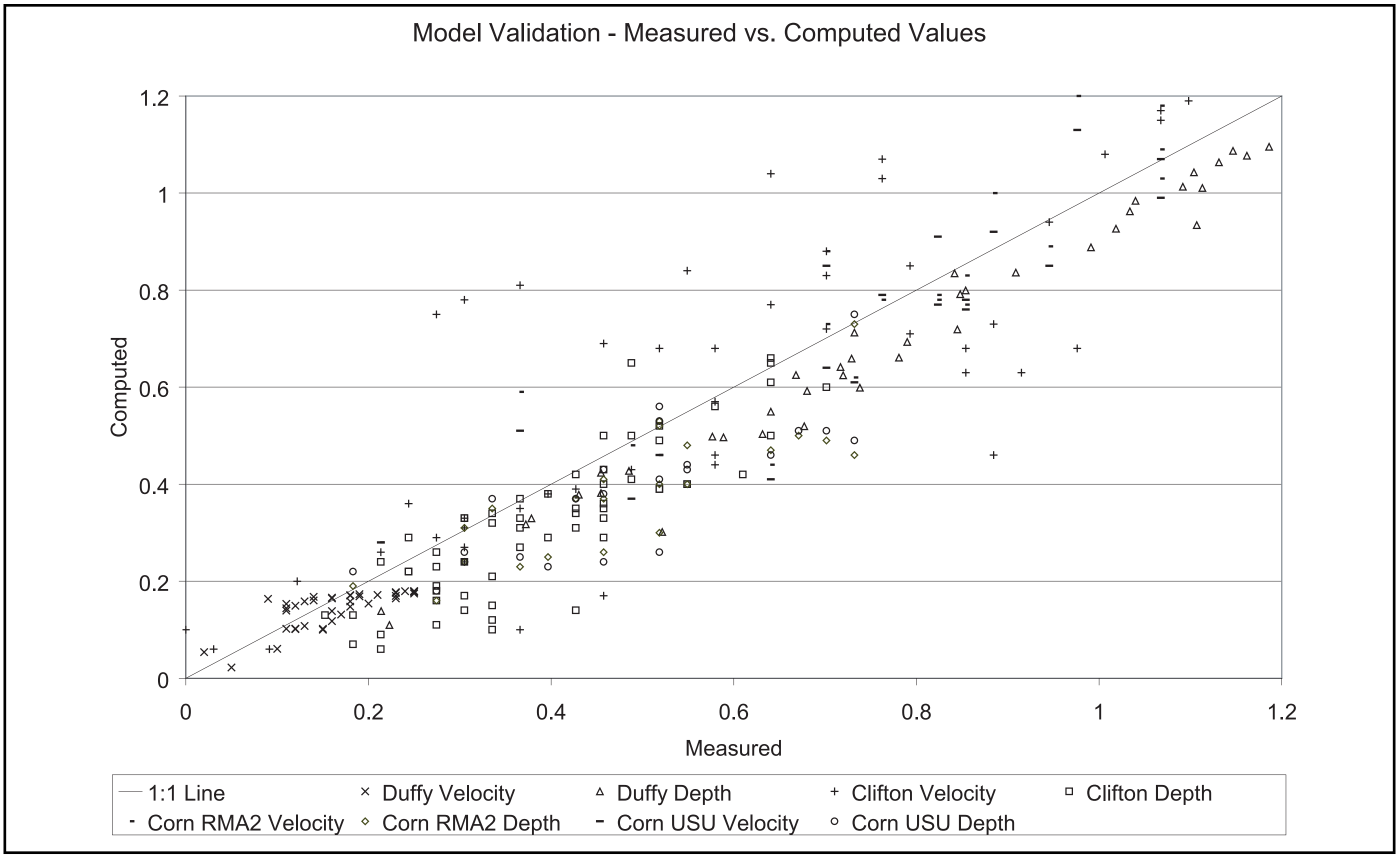


FIGURE I-4. Measured vs. modeled depth and velocity for Duffy, Corn Lake, and Clifton.

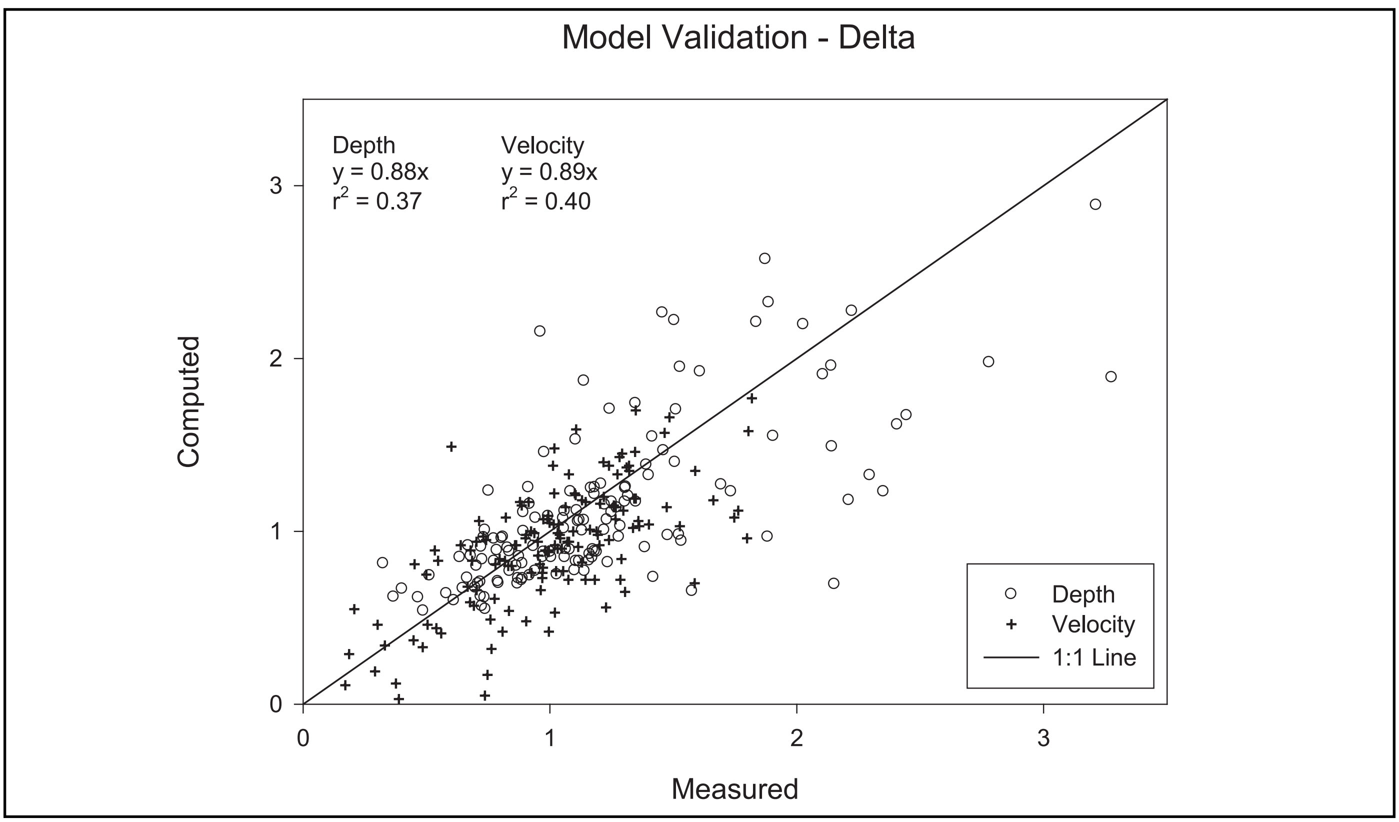


FIGURE I-5. Measured vs. modeled depth and velocity for Delta.

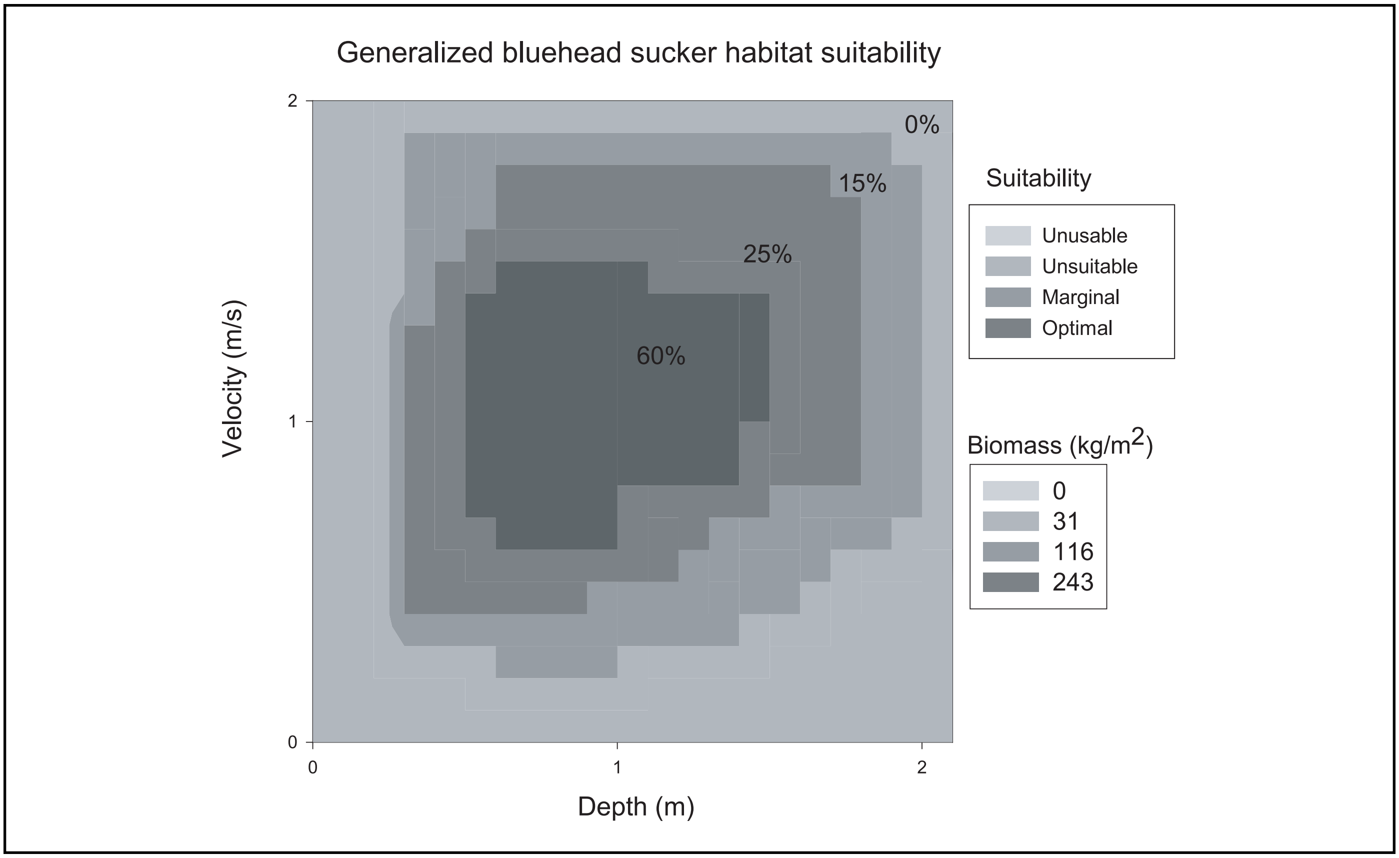


FIGURE I-6. Generalized habitat suitability criteria for bluehead sucker.

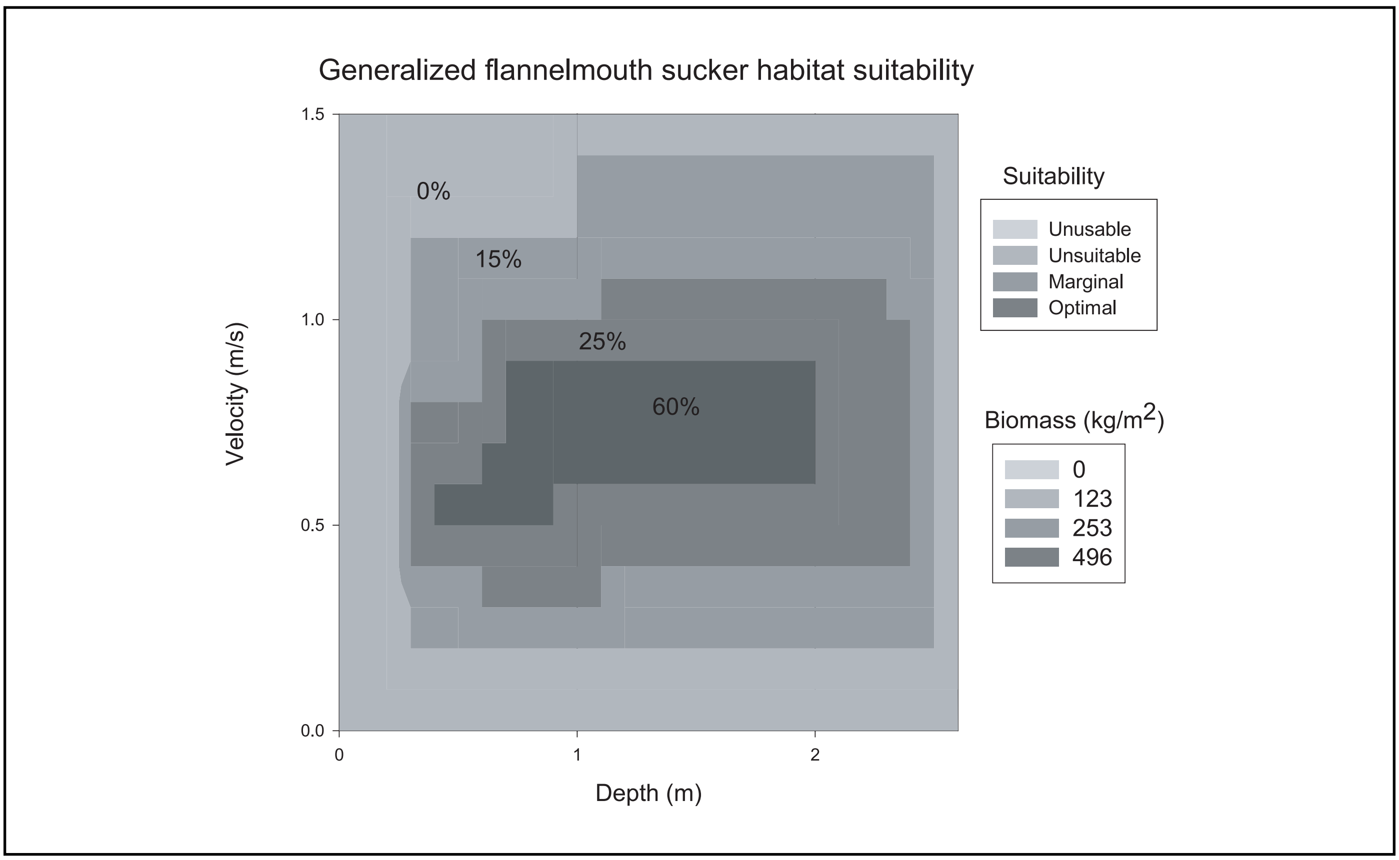


FIGURE I-7. Generalized habitat suitability criteria for flannelmouth sucker.

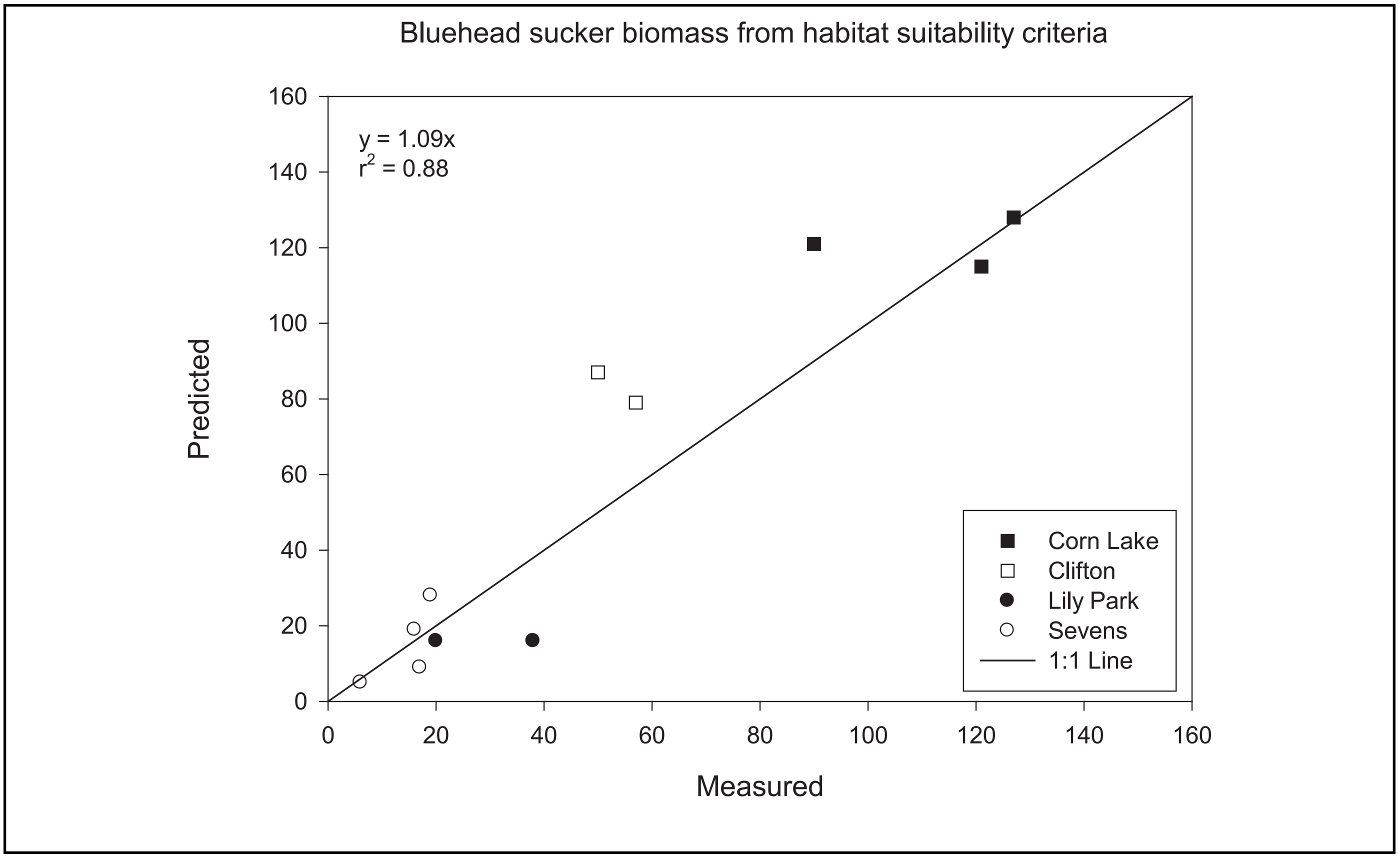


FIGURE I-8. Habitat suitability dataset relationship between measured and predicted bluehead biomass.

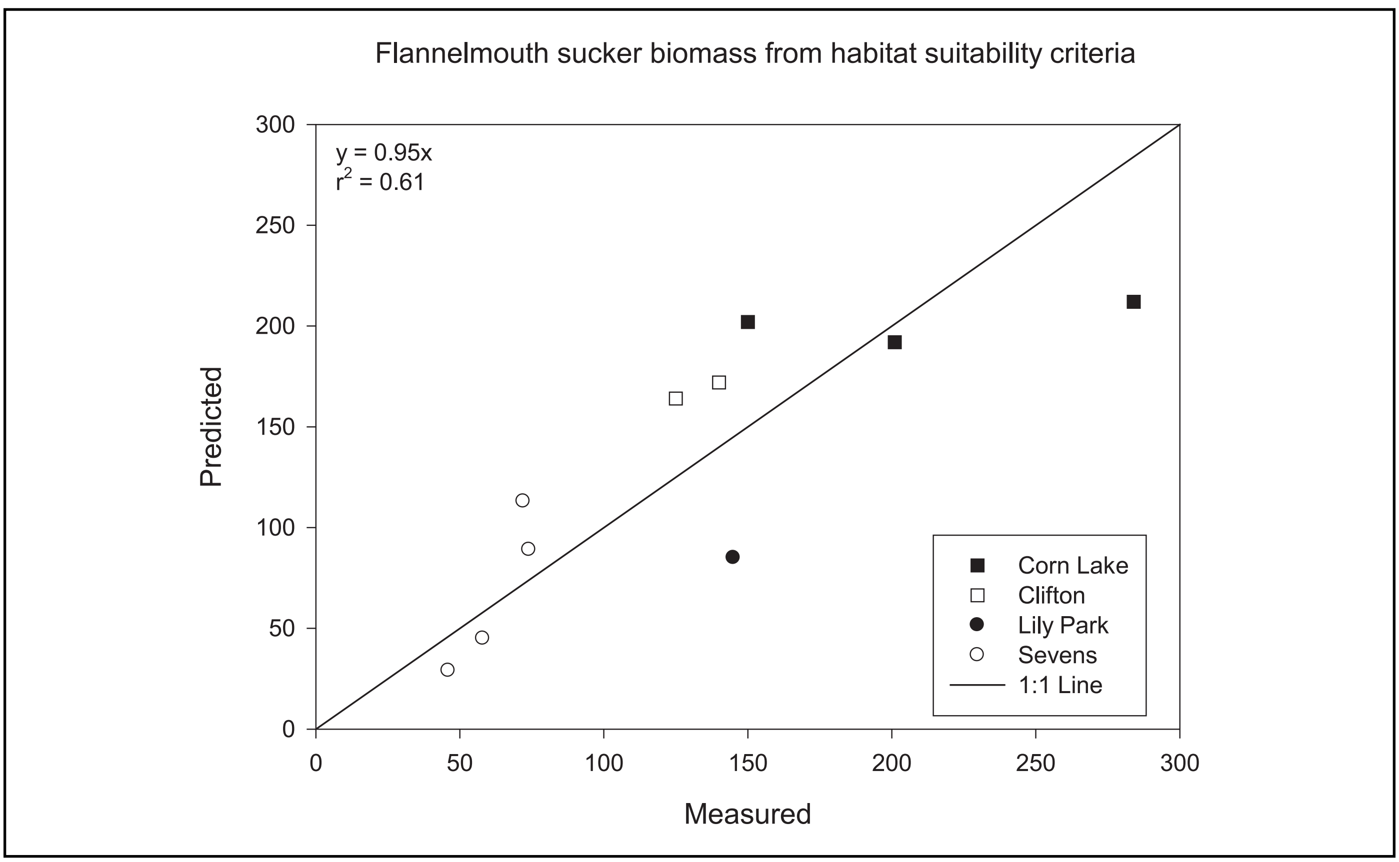


FIGURE I-9. Habitat suitability dataset relationship between measured and predicted flannelmouth biomass.

Validation of Habitat Suitability

Using the generalized habitat suitability criteria developed, 2D hydraulic modeling results and fish data collected between 2002 and 2004; we were able to validate the methodology by predicting biomass as a function of discharge and then comparing it to measured biomass. Predictions were made using the 60-day low flow for each year in which the fish were caught. As shown in Figures I-10 and I-11, the relationship between measured and predicted biomass for bluehead and flannelmouth sucker in the validation period is similar to that expressed in the original dataset. For bluehead sucker, the coefficient of determination (r^2) for the validation dataset is 0.69 (n=11) compared with 0.88 for the curve development period (combined r^2=0.75). For flannelmouth sucker, r^2 between measured and predicted biomass is 0.45 (n=11) for the validation dataset compared to 0.61 for the original dataset (n=10).

In both cases, the relationship decreased during the validation phase. Data analysis showed the inclusion of the Gunnison River data had a negative influence on measured vs. predicted biomass correlations. The most apparent reasons for the Gunnison River data to result in downgraded correlations are: 1) a relatively poor relationship between measured and calculated depth and velocity (Figure I-5); and 2) the Gunnison rivers high year-to-year variability in biomass estimates (Table I-2, explained in Anderson and Stewart 2006b) and 3) the fact that higher Gunnison River summer flows yield deeper and swifter habitat conditions than those from rivers where the habitat suitability criteria were developed. When data collected on the Yampa and Colorado Rivers during the validation period are analyzed alone, the coefficient of determination between measured and predicted biomass for bluehead and flannelmouth sucker are 0.90 and 0.74, respectively (n=7).

Validation Period Habitat Suitability Criteria

As previously noted, one issue with the development of habitat suitability criteria is that they are only valid over the range of depths and velocities from which they were developed. The Gunnison River, with its high summer base flows, was deeper and faster than either the Yampa or Colorado River during the period of fish data collection. To evaluate whether Gunnison River data were significantly different than the Yampa and Colorado River data, mean meso-habitat depth and velocity from the Gunnison River were plotted against mean depth and velocity from the original dataset collected on the Yampa and Colorado Rivers. Figures I-12 and I-13 show that mean meso-habitat depth and velocity on the Yampa, Colorado, and Gunnison overlap considerably; but there are ranges of depth and velocity that were only exhibited at the Gunnison River sites. Given differences in mean depth and velocity between the rivers, it was thought that habitat suitability criteria developed from the Yampa and Colorado might be inappropriate for use on the Gunnison. Data smoothing of biomass as a function of depth and velocity using the original and revised data (original + Gunnison River), shows slightly different patterns of optimal habitat (60 percent, Figures I-12 and I-13).

During the development of the revised habitat suitability matrices, it became clear that the inclusion of unsuitable and marginal habitat (<15 percent and 25 percent of total biomass respectively) had little positive affect on the predictive capacity of the suitability criteria. As a result, those categories were dropped and the revised suitability matrix was binomial with only habitat and non-habitat categories (Figures I-14 and I-15).

The development of revised habitat suitability criteria that included biomass data from the Gunnison River did not increase the predictive capacity of the model. Original suitability criteria explained 75 percent (n=22) and 43 percent (n=22) of the bluehead and flannelmouth biomass respectively, though the model slightly under predicted biomass for both species. In contrast, the revised model that included Gunnison River data explained only 66 percent (n=22) and 40 percent (n=22) of bluehead and flannelmouth biomass respectively (Figure I-16, Figure I-17). Thus, for bluehead the revised matrices had less predictive power than the original. For flannelmouth, the two habitat suitability matrices were equivocal. When Lilly 2000 and Escalante are removed as outliers the relationship for the new revised suitability matrix increases to r^2=0.62 (predicted = 0.99*measured, n=19).

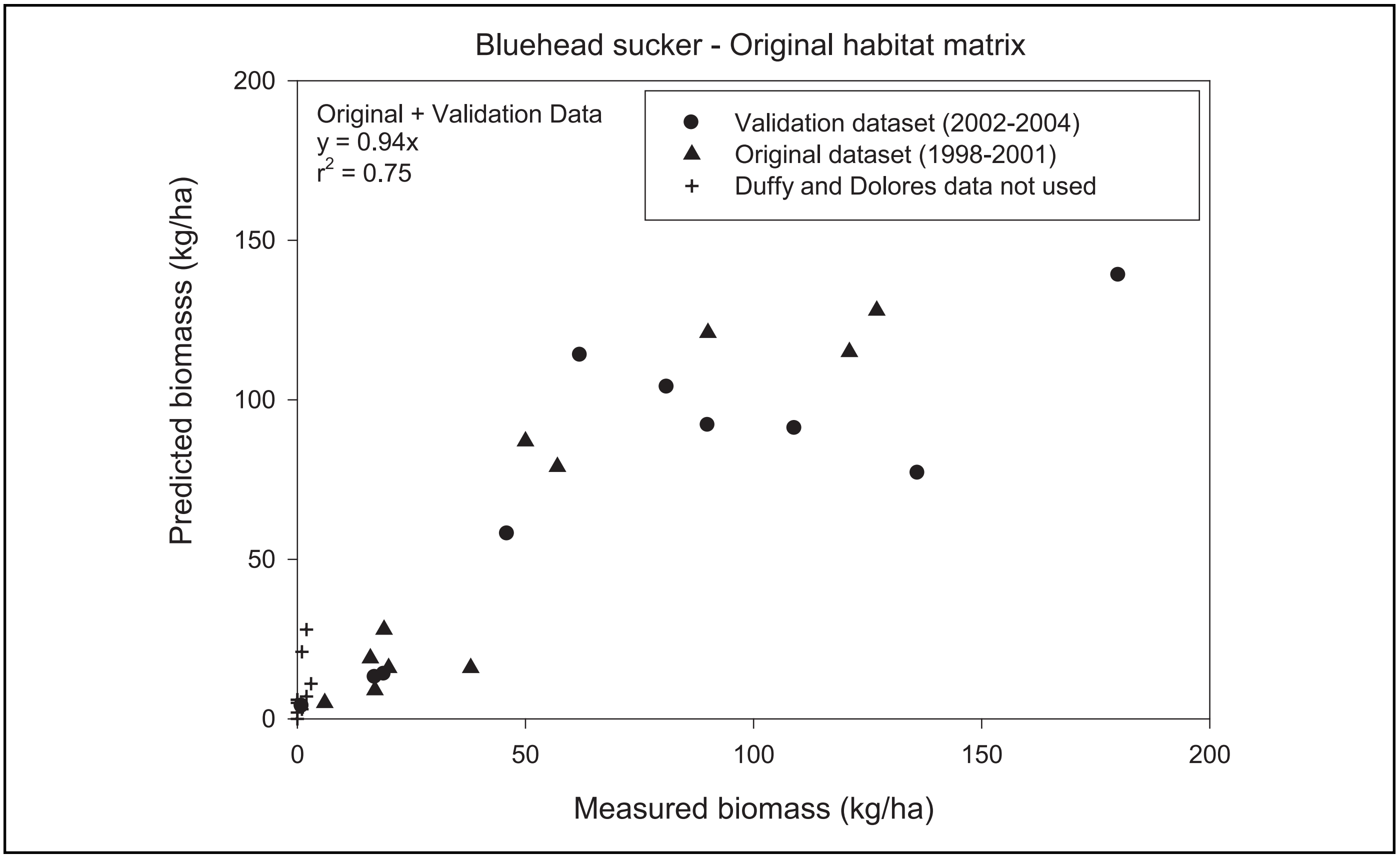


FIGURE I-10. Measured vs. predicted bluehead sucker biomass.

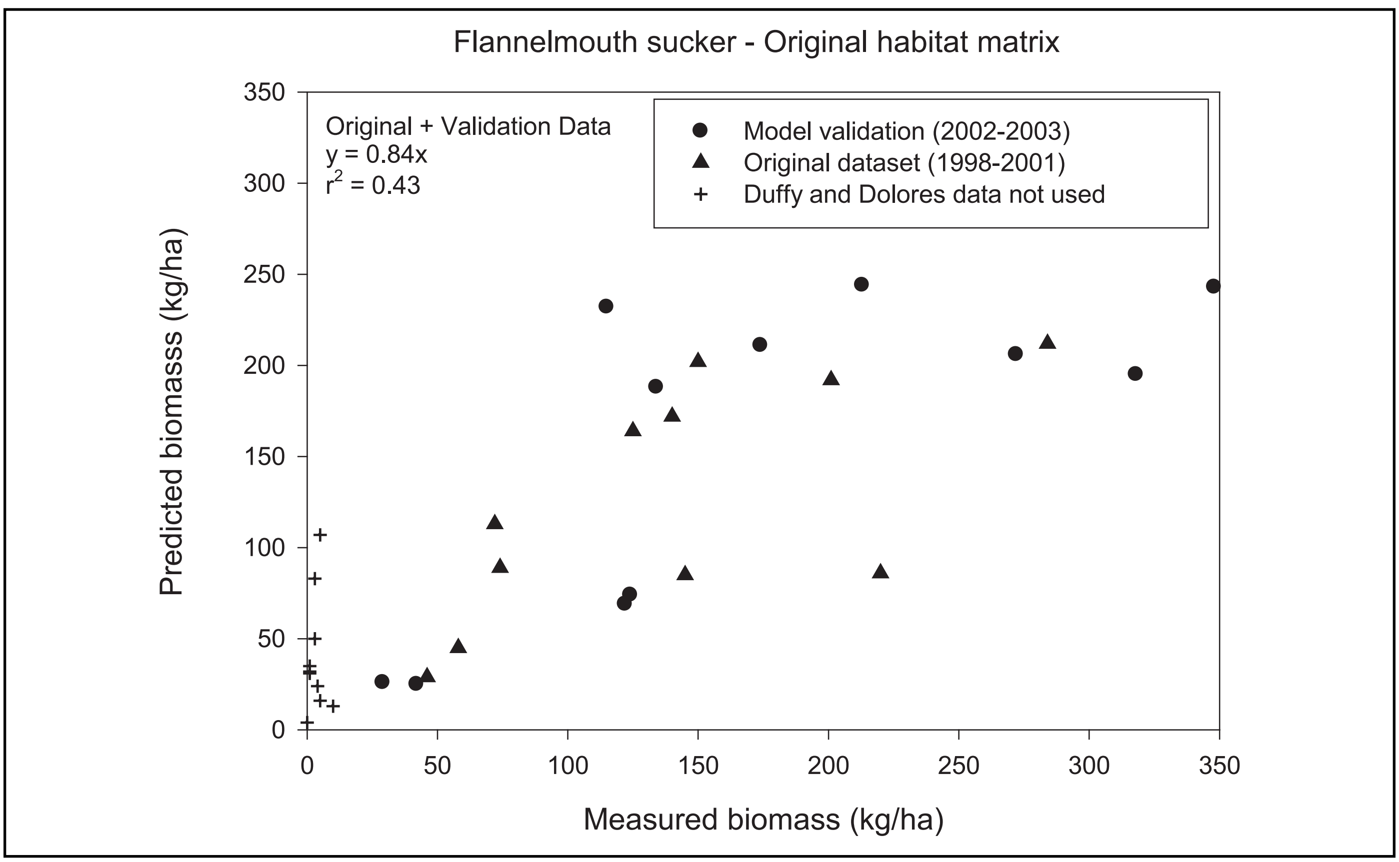


FIGURE I-11. Measured vs. predicted flannelmouth sucker biomass.

TABLE I-2. Measured (estimate) vs. predicted biomass for original and validation period data.

			Bluehead biomass (kg/ha)		Flannelmouth biomass (kg/ha)	
Site	Year	60-day discharge (cfs)	Estimate	Predicted	Estimate	Predicted
Escalante	**2005**	**931**	**90**	**99**	**115**	**299**
Escalante	**2004**	**669**	**136**	**93**	**174**	**276**
Delta	**2005**	**931**	**180**	**140**	**213**	**300**
Delta	**2004**	**669**	**62**	**134**	**348**	**300**
Big Gyp	2005	37	0	4	10	3
Big Gyp	2004	22	0	1	0	1
Big Gyp	2001	42	1	6	5	4
Big Gyp	2000	52	0	11	4	11
Duffy	2004	153	0	13	1	6
Duffy	2003	152	0	13	1	6
Duffy	2001	160	2	14	1	8
Duffy	2000	199	3	21	3	17
Duffy	1999	290	1	37	3	71
Duffy	1998	350	2	50	5	111
Sevens	**2004**	**153**	**1**	**5**	**29**	**17**
Sevens	**2003**	**152**	**1**	**5**	**42**	**16**
Sevens	2001	160	6	6	46	21
Sevens	2000	199	17	11	58	47
Sevens	1999	290	16	36	74	115
Sevens	1998	350	19	50	72	146
Lily	**2004**	**170**	**17**	**13**	**122**	**65**
Lily	**2003**	**180**	**19**	**13**	**124**	**69**
Lily	2001	203	20	15	145	79
Lily	2000	206	38	15	220	80
Clifton	**2003**	**601**	**46**	**78**	**134**	**247**
Clifton	2001	927	57	94	125	205
Clifton	2000	1090	50	100	140	208
Corn Lake	**2004**	**850**	**81**	**113**	**272**	**251**
Corn Lake	**2003**	**700**	**109**	**106**	**318**	**234**
Corn Lake	2001	1000	121	118	284	262
Corn Lake	2000	1200	90	115	150	256
Corn Lake	1999	1600	127	111	253	238

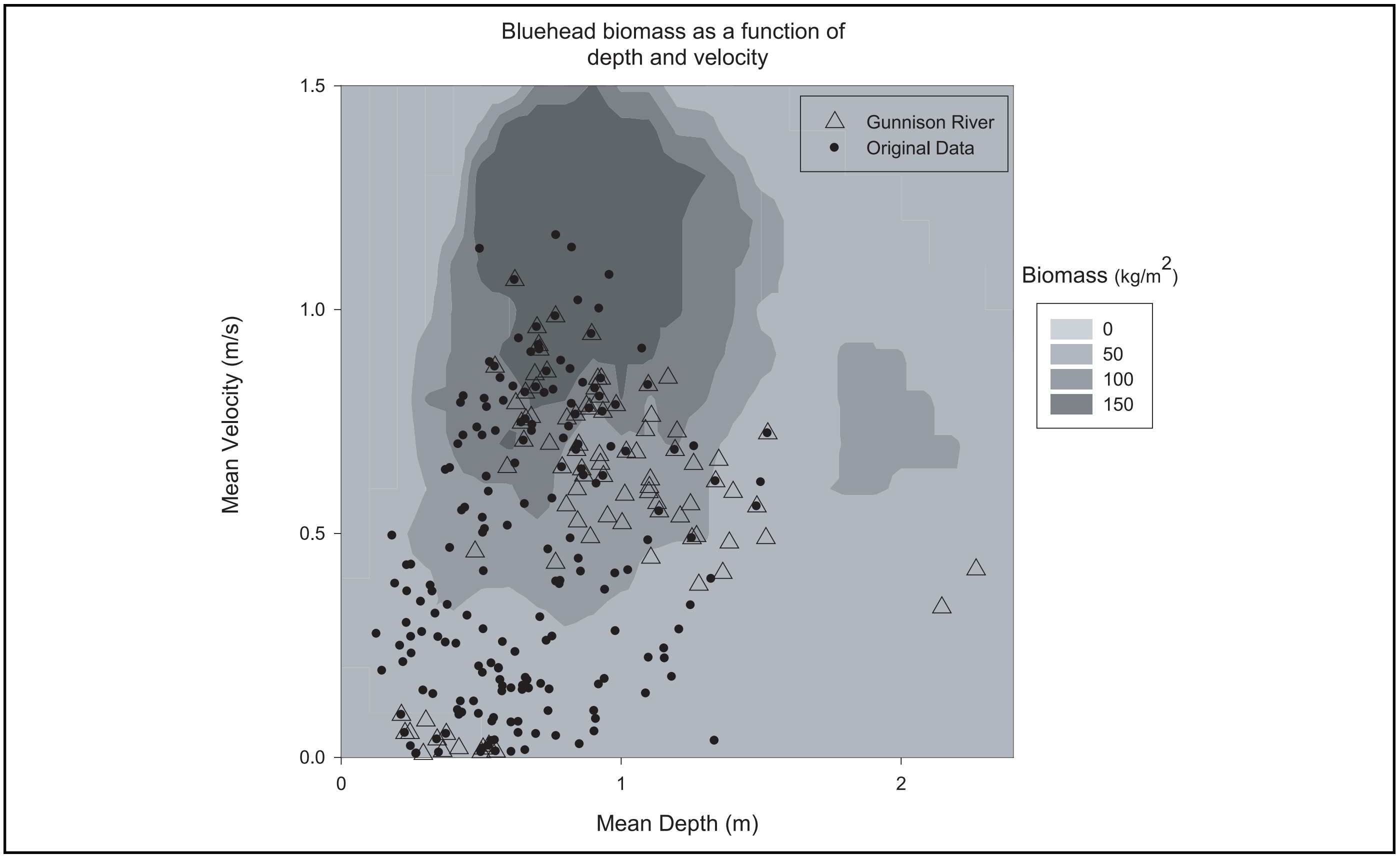


FIGURE I-12. Measured vs. predicted bluehead sucker biomass.

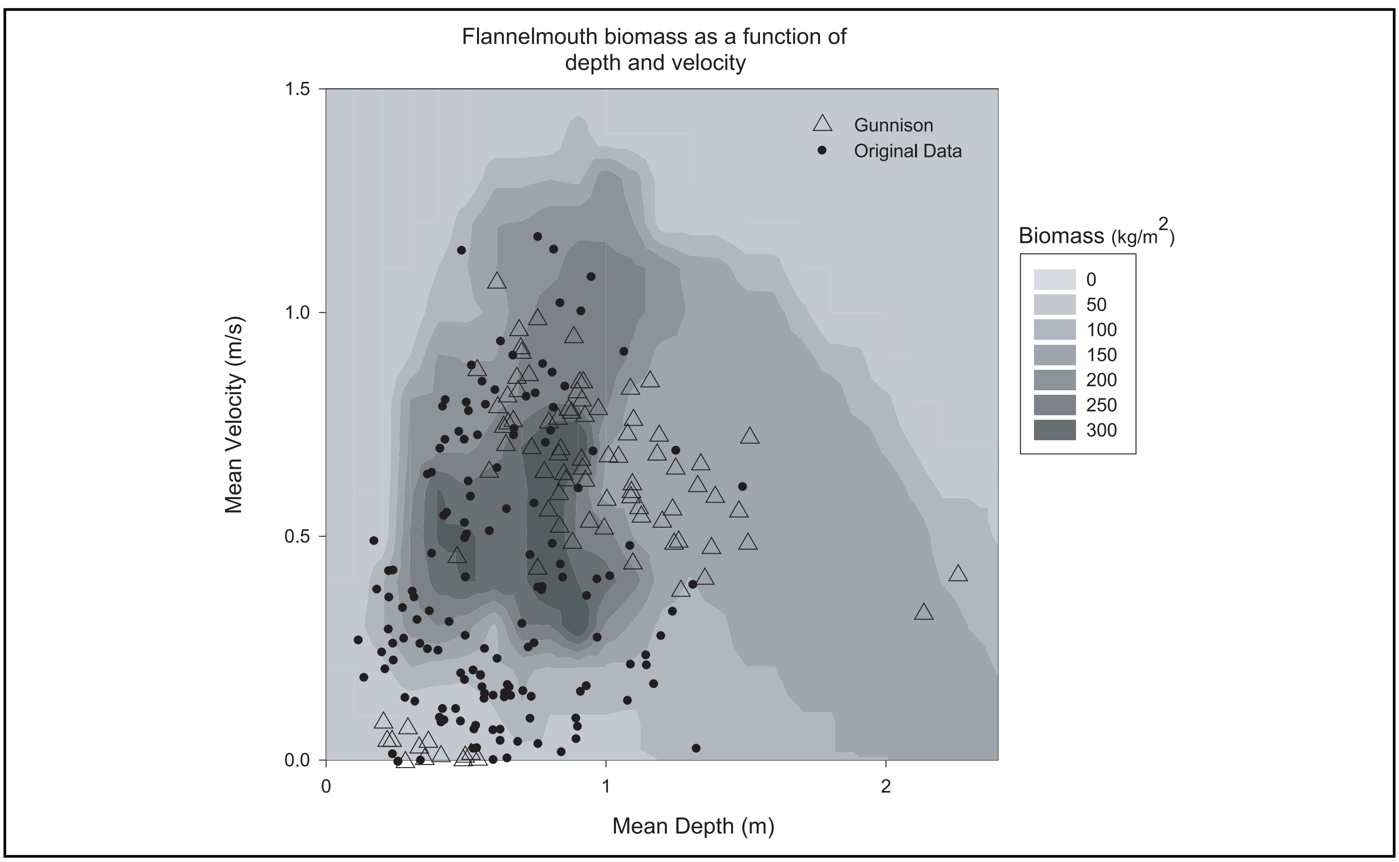


FIGURE I-13. Measured vs. predicted flannelmouth sucker biomass.

Habitat Suitability as a Function of Discharge

Instream flow incremental methodologies use hydraulic models and habitat suitability criteria to quantify the incremental effect of discharges on habitat suitability. These incremental changes are typically expressed as curves for a given species and site of interest. As shown in Figures I-18, I-19 and I-20; habitat suitability as a function of discharge is similar among rivers, though summer base flows and fish biomass vary significantly. Habitat suitability increases rapidly with discharge at each site from the lowest modeled discharge, but at some point the rate of increase begins to slow. For flannelmouth sucker, maximum habitat availability does not appear to be associated with base flows in the range of 2000 cfs, but rather intermediate flows.

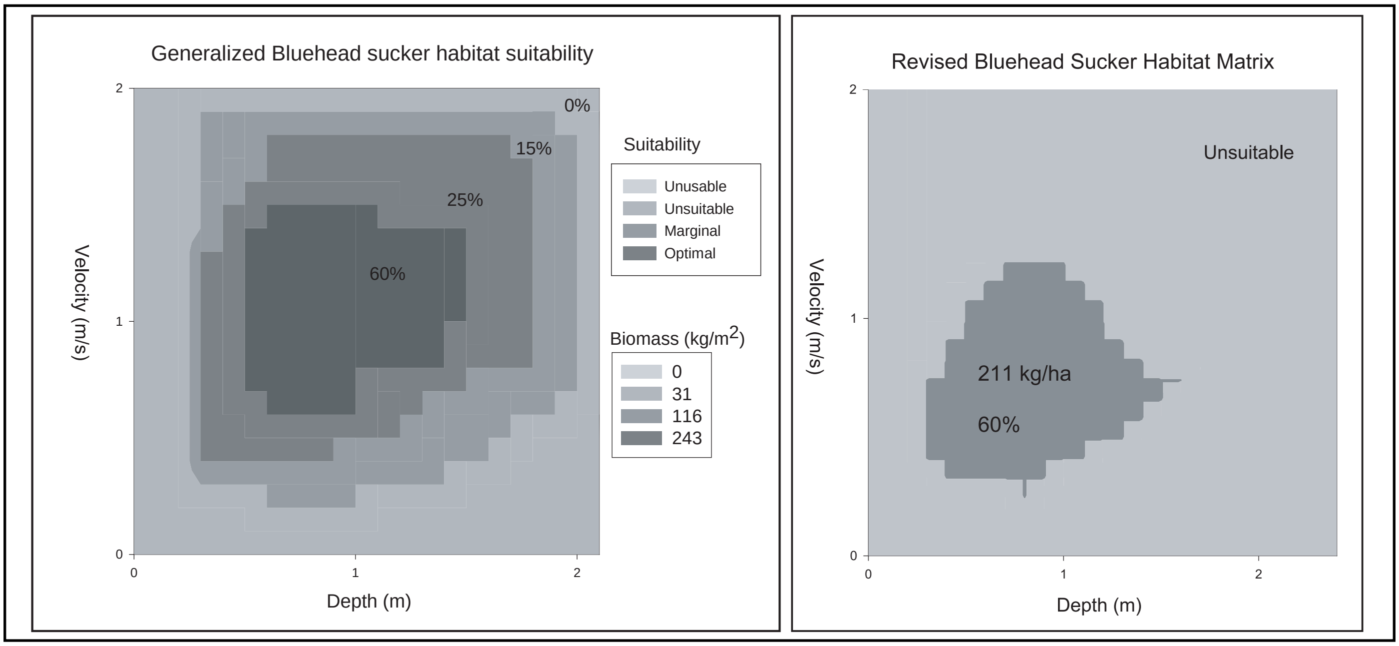


FIGURE I-14. Measured vs. predicted bluehead sucker biomass.

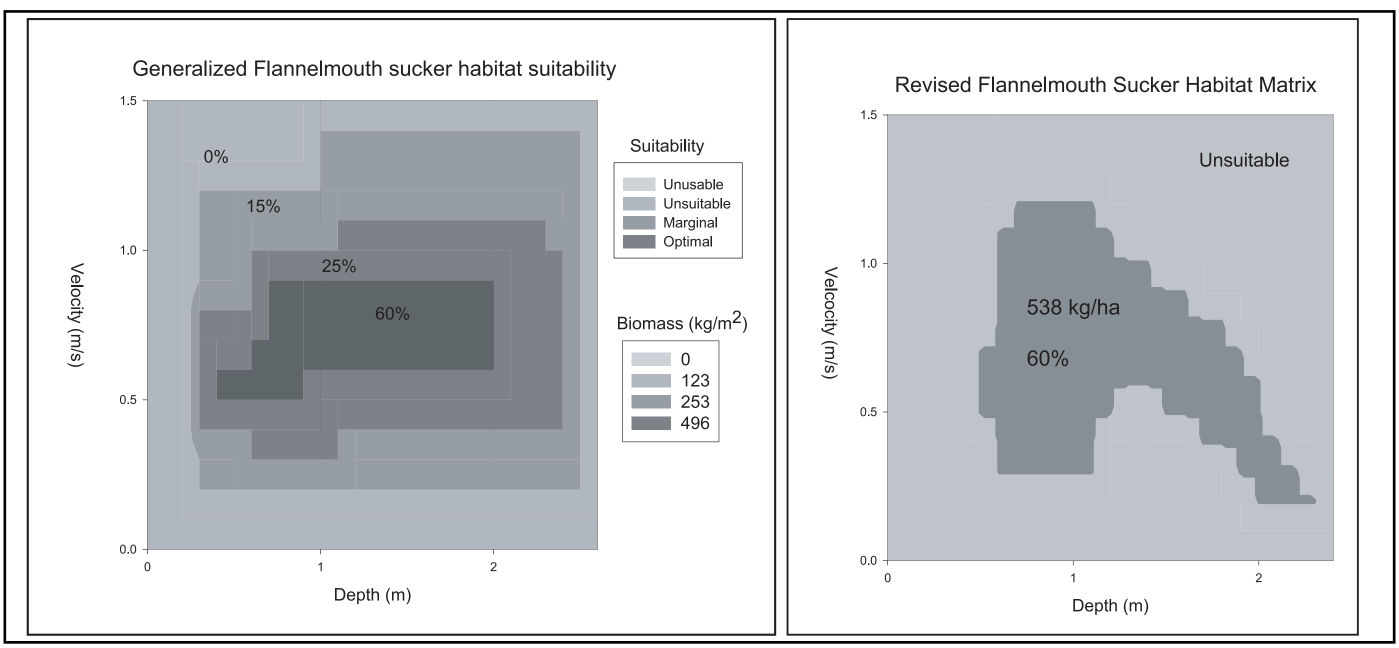


FIGURE I-15. Measured vs. predicted flannelmouth sucker biomass.

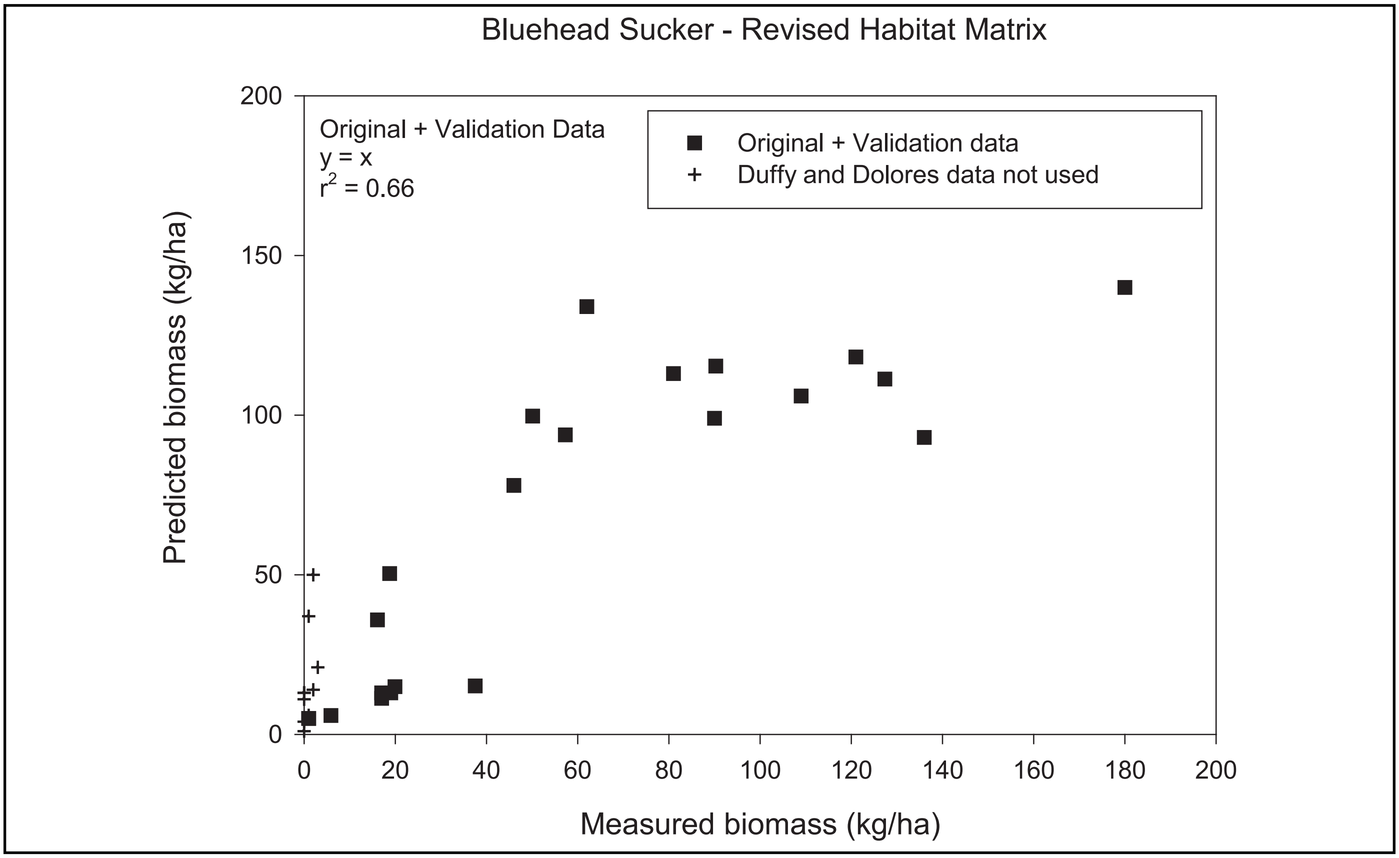


FIGURE I-16. Measured vs. predicted bluehead sucker biomass using revised habitat matrix.

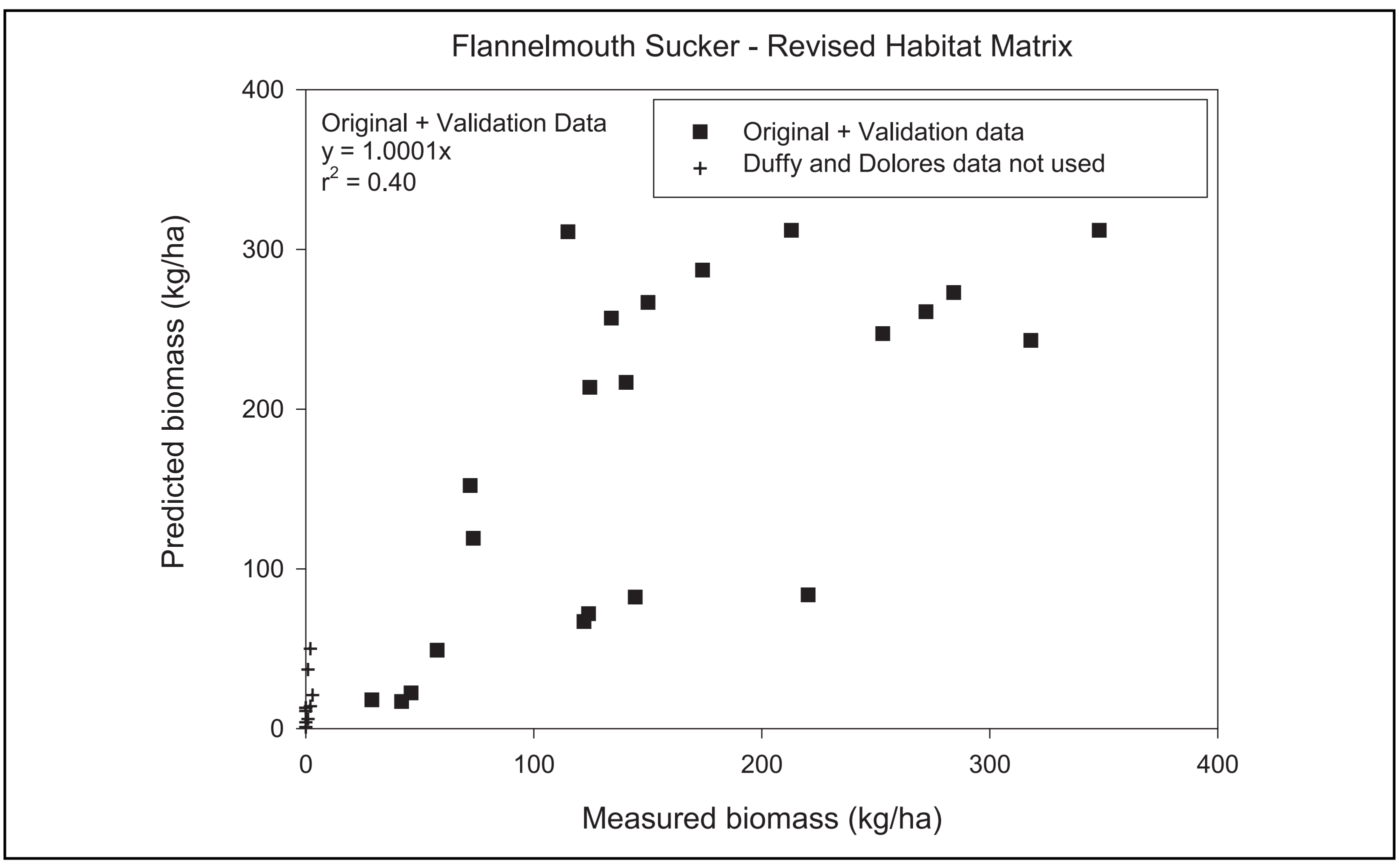


FIGURE I-17. Measured vs. predicted flannelmouth sucker biomass using revised habitat matrix.

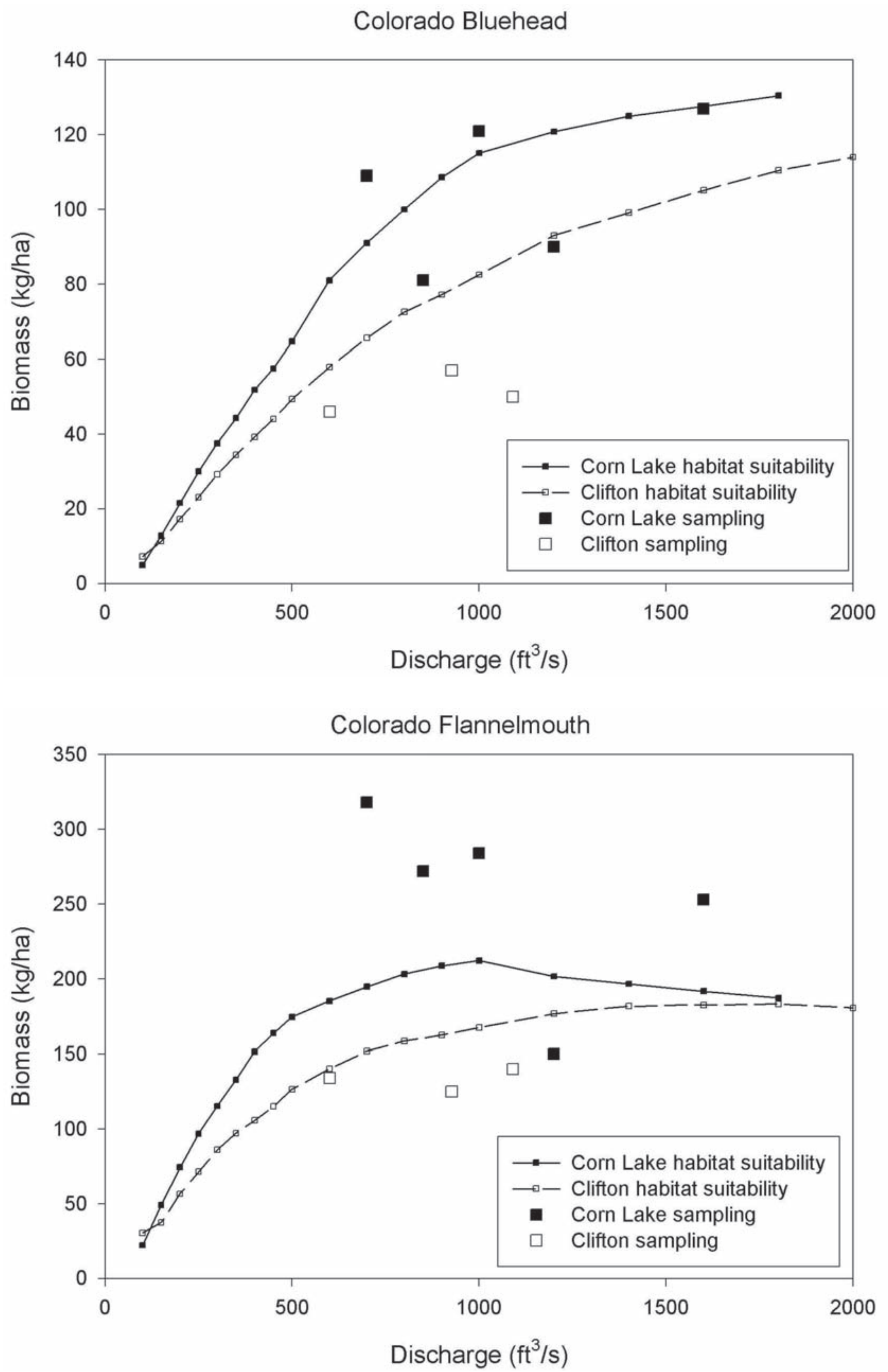
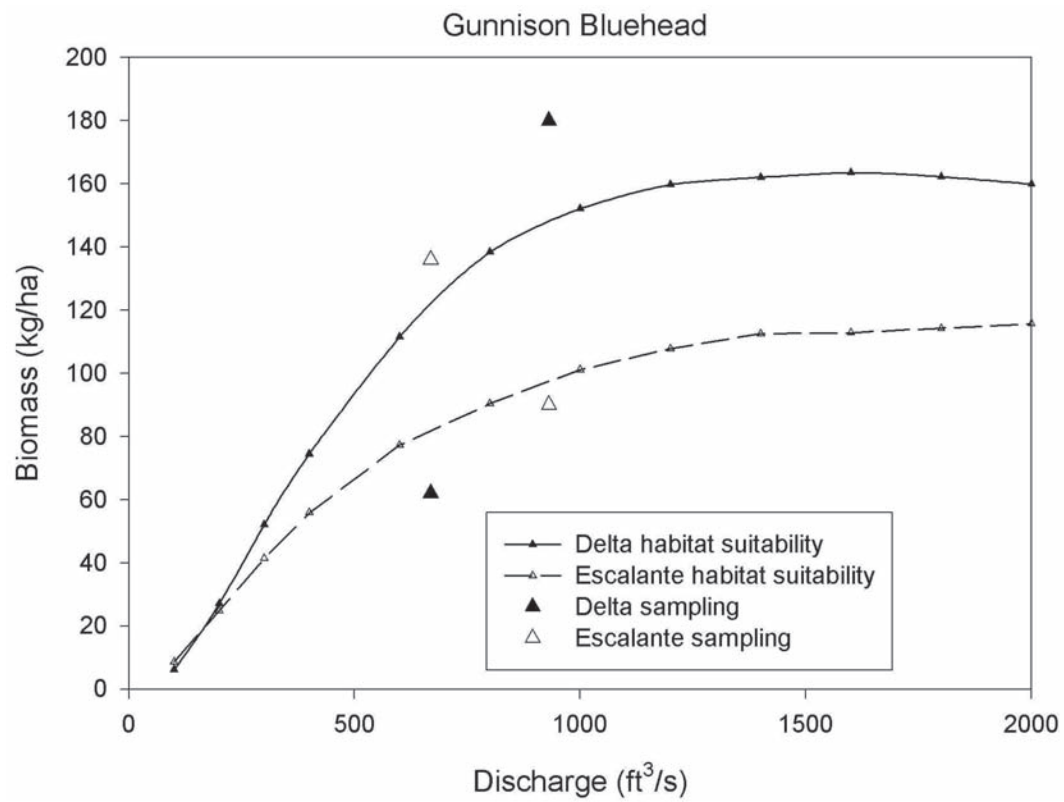


FIGURE I-18. Colorado River habitat suitability curves for bluehead and flannelmouth sucker showing predicted biomass as a function of discharge (curves) and measured biomass (symbols).



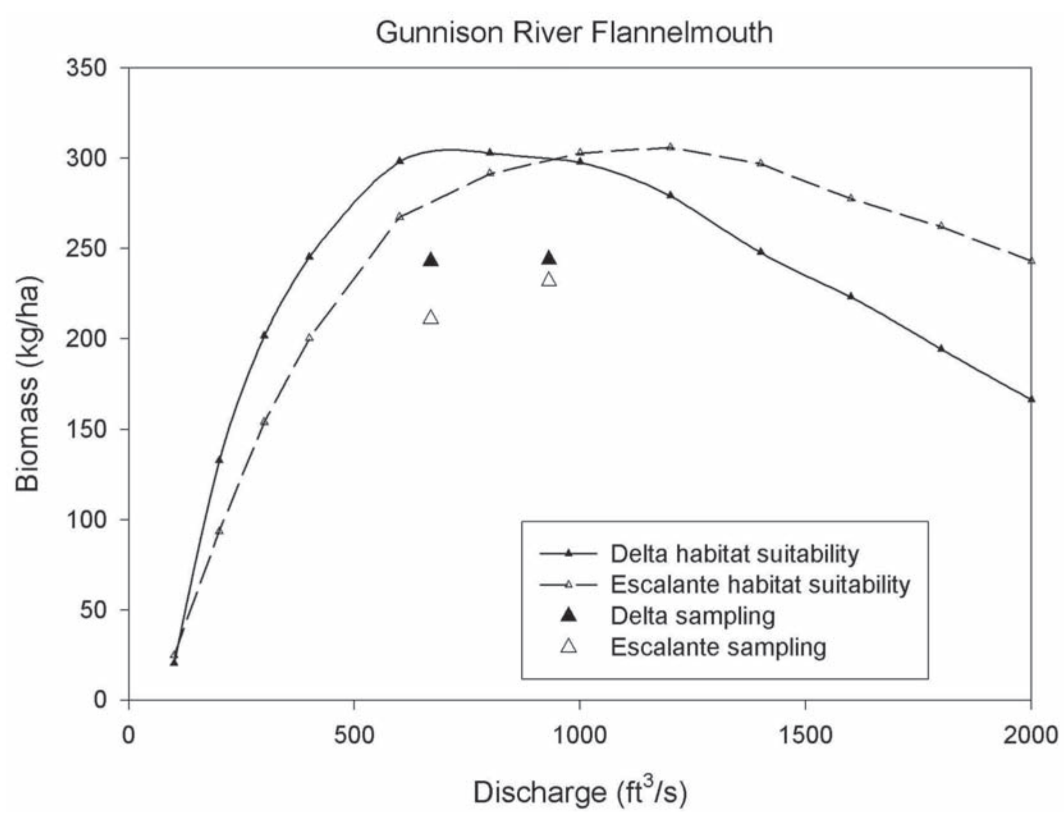


FIGURE I-19. Gunnison River habitat suitability curves for bluehead and fannelmouth sucker showing predicted biomass as a function of discharge (curves) and measured biomass (symbols).

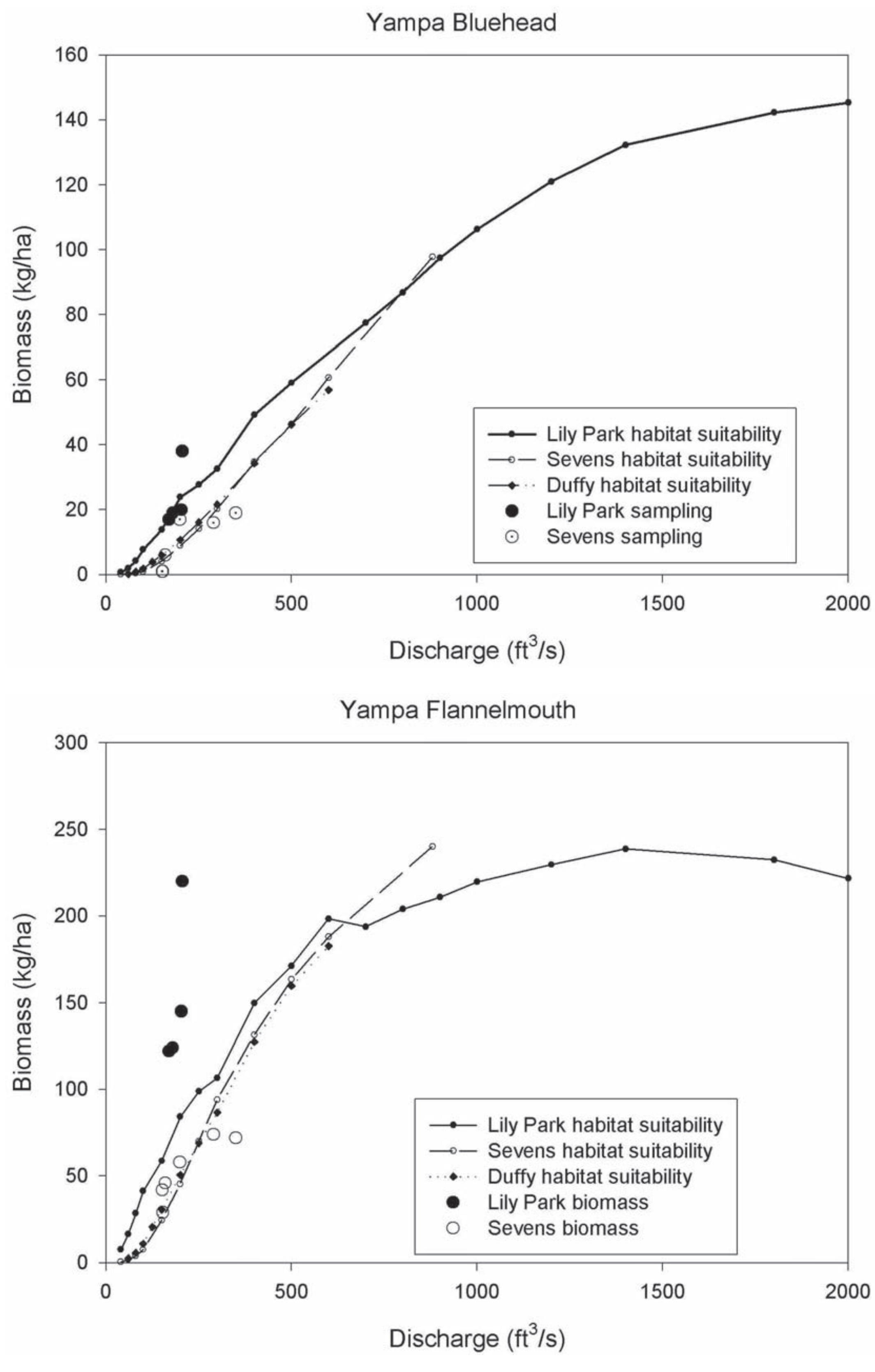


FIGURE I-20. Yampa River habitat suitability curves for bluehead and flannelmouth sucker showing predicted biomass as a function of discharge (curves) and measured biomass (symbols).

DISCUSSION

Using 2D modeling results and meso-habitat biomass estimates, we tested the hypothesis that adult fish biomass on the Yampa and Colorado Rivers could be predicted as a function of hydraulic variables during periods of low discharge. We found significant relationships between depth, velocity and bluehead / flannelmouth sucker biomass. Three-dimensional plots of depth, velocity and biomass show that certain ranges of depths and velocities have significantly higher adult fish biomass than do others. When data are smoothed into a regular matrix, biomass can be predicted as a function of depth and velocity. Results show good agreement between predicted and measured biomass at the meso-habitat level for bluehead and flannelmouth sucker.

By applying a suitability class to each depth/velocity combination generated by the 2D hydraulic models and summing the predicted biomass over the entire site, we were able to estimate biomass for each site and discharge. Again, measured and observed biomasses at the site scale were strongly correlated, although the suitability model appears to underestimate flannelmouth biomass at the site level by nearly 20 percent.

Plots of predicted biomass as a function of discharge are similar between the rivers. The Yampa, Colorado and Gunnison Rivers have the same fish communities, similar morphologies, yet widely different base flows and native (and total) fish abundances. These data strongly suggest that low summer base flows are acting to limit adult native fish biomass on the Yampa River. While we do not rule out that other mechanisms including hybridization, channel alteration and/or water quality changes may be affecting native fish biomass on the Yampa, we can find no evidence to suggest that adult bluehead and flannelmouth sucker biomass could not be increased by increasing summer base flows.

While we attempted to develop physical habitat suitability indices for roundtail chub, no relationship between roundtail chub biomass (or density) and water depth / velocity could be established. Preliminary evidence appears to support an alternate hypothesis that roundtail chub biomass can be predicted as a function of habitat heterogeneity at the reach scale (riffle to riffle or greater). Roundtail chub are predators that use different meso-habitats for different activities (patrolling, feeding and holding) and more diverse habitats may allow roundtail chub to expend less energy traveling between suitable meso-habitats units.

Benefits and Limitations of the Study Approach

Biological data used in this study were collected over multiple years and sites on three different rivers. Although these data took considerable time to collect, consistency in the fish community through time suggests a strong dynamic relationship with habitat conditions. Habitat suitability predicted as a function of depth and velocity suggest similar habitat potential among rivers (with the exception of Duffy which was significantly affected by hybridization), yet the data shows that measured biomass varies significantly. By combining data from the Yampa and Colorado rivers in development of the suitability criteria, we were able to incorporate a wide range of biomass estimates. Consistency in predicted biomass and habitat availability between sites and rivers suggests that the suitability indices are relatively robust and can be applied to other sites with similar morphology and fish community structure.

Two-dimensional flow models were used for calculating hydraulic variables. Modeled sites exhibited significant lateral variations in depth and velocity that could not have been accounted for with traditional 1D or quasi-2D model approximations. It is interesting to note, however, that although depth and velocity were defined at one meter increments both longitudinally and laterally, we found mean meso-habitat depth and velocity adequate for developing bluehead and flannelmouth sucker habitat suitability indices. It is reasonable to assume that mean depth and velocity could have been calculated in much less time using 1D models with using closely spaced cross-sections (cross-sections spaced within and between meso-habitat units).

A few major advantages that 2D models provided were expressed by our ability to validate hydraulic modeling results, map hydraulic data at very high spatial resolutions (1x1 meter) and to extrapolate habitat suitability into biomass estimates by mapping suitability as a function of spatially explicit depth and velocity. Meso-habitats were chosen as the biological scale of interest because they were the smallest unit from which fish community structure could be sampled and expected to demonstrate consistency through time. Because meso-habitat units are spatially explicit (i.e., can be mapped), biomass estimates collected at the meso-habitat scale can be correlated with any other congruent spatially explicit dataset (i.e., datasets with spatial scales that are multiples of meso-habitat scale).

A significant limitation of this study approach is that it cannot be used to evaluate effects of low discharge on very rare species. Colorado Pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*) are both federally listed endangered species whose historic range was inclusive of the Colorado and Yampa river study sites. We explicitly assume that biomass can be used to discriminate between different suitability at the sub-site scale; within a site, highly suitable habitats will contain higher biomass for any given species than poorly suited habitats. Colorado pikeminnow or razorback sucker are so rare that few were ever caught in the study area and none were re-captured to provide site-level biomass estimates. Other problems include the need for accurate modeling of river hydraulics and spatially explicit fish biomass estimates. While the former is primarily a quality control issue, the latter represents a significant field sampling problem. Current fish sampling methodologies for obtaining community biomass estimates have poor spatial resolution and catch per unit effort is affected by non-hydraulic variables including water turbidity and depth. Until our ability to get high-resolution (spatial and temporal) fish data improves, it will be difficult to fully utilize data provided by multi-dimensional hydraulic models.

CONCLUSIONS

A stated goal of this project was to evaluate 2D modeling and to recommend a standardized instream flow methodology for use by the State of Colorado. Based on the findings reported here and in the previous completion reports, it is clear that the combination of 2D flow modeling with meso-habitat community biomass estimates in an IFIM type strategy represents a substantial improvement in instream flow assessment over most previously published methods (Stewart et. al., 2005). This study addresses three of the four primary criticisms of IFIM; 1) relationships between WUA and population response have been established, 2) the capability of 2D models to explicitly predict flow components has been demonstrated and 3) the predictive capability of the methodology has been demonstrated. Only the focus on single species and life stages was not addressed though the use of 2D models and community biomass data.

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