THESIS

TWO-DIMENSIONAL HYDRAULIC MODELING FOR MAKING INSTREAM-FLOW RECOMMENDATIONS

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY GREGORY STEWART ENTITLED TWO-DIMENSIONAL HYDRAULIC MODELING FOR MAKING INSTREAM-FLOW RECOMMENDATIONS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

TWO-DIMENSIONAL HYDRAULIC MODELING FOR MAKING INSTREAM-FLOW RECOMMENDATIONS

Of primary concern in most instream flow studies is the availability of physical habitat that meets the needs and preferences of aquatic species. In warmwater rivers, where fish display generalized habitat use preferences and there is high species diversity, the applicability of traditional instream flow methodologies has been called into question. A new methodology is required that accounts not only for the temporal and spatial variability of physical habitat, but does so on a scale relevant to fish.

Attempts have recently been made to increase the accuracy of instream flow modeling by using two-dimensional flow models. Two-dimensional models should offer a significant improvement over other instream flow methodologies by increasing spatial resolution and allowing for better representation of physical habitat. This increased resolution will, in theory, allow for the development of habitat suitability criteria based on patterns of habitat utilization and availability at the community level.

In this study, two stream reaches were surveyed using the latest technology for use in a 2-D model. Two-dimensional modeling results were used to map meso-habitat units, which were then correlated with adult fish abundance estimated by electro-shocking. As expected, the abundance of some species was significantly correlated with the abundance of some types of physical habitat. Of perhaps greater interest was that, for a number of fish species, fish abundance was significantly correlated with indices of habitat heterogeneity. These results suggest that for some species habitat structure may be as, or more, important than habitat availability.

The primary objective of the study was to assess the relative merits of 2-D modeling for making instream flow recommendations. The findings suggest that while 2-D modeling does offer increased spatial resolution and insight into habitat dynamics, it does so at a large cost in terms of time and effort. It can be expected that while there will be a continued increase in the use of these methodologies as technology advances and the value of water resources increases, use of 2D models for assessing fish habitat will not replace existing instream methodologies anytime in the near future.

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Chapter I - INTRODUCTION

Of primary concern in most instream flow studies is the availability of physical habitat that meets the needs and preferences of aquatic species. In warmwater rivers, where fish fail to display strong habitat preferences and species diversity is high, the applicability of traditional instream flow methodologies is highly questionable (Bowen *et al*, 1998). A new methodology is required that accounts not only for the temporal and spatial variability of physical habitat, but does so on a scale relevant to fish (Leclerc *et al*, 1995).

Attempts have recently been made to increase the accuracy of instream flow modeling by using two-dimensional flow models. Two-dimensional models should offer a significant improvement over other instream flow methodologies by providing a more accurate representation of the hydraulic characteristics of fish habitat (Ghanem *et al*, 1996). The spatially explicit nature of two-dimensional models will, in theory, allow for the development of habitat suitability criteria based on patterns of habitat utilization and availability at the community level (Bovee, 1996a).

1.1 Background

Instream flows are flows left in the river channel, as opposed to being diverted for out-of-stream uses. The need to protect instream flows for aquatic habitat was recognized following the water development period of the mid-20th century as biologists and hydrologists began to see a decline in fish resources. During the 1960’s and early 1970’s several instream flow assessment methods were developed based on hydrologic analysis of water supply coupled with empirical observations of habitat quality and an understanding of riverine fish ecology (Stalnaker, 1994). The goal of these methodologies was to benefit fish and wildlife.

Currently, two of the most popular instream flow assessment methods in the United States are the wetted perimeter/discharge (inflection point) method and the physical habitat simulation component (PHABSIM) of the instream flow incremental methodology (IFIM) (Reiser *et al*., 1989). The inflection point method is based on the fact that wetted perimeter does not generally grow in a linear relationship with discharge, but rather grows as a log or power function. When discharge is plotted against wetted perimeter, there is generally an inflection point in the curve, below which wetted perimeter grows rapidly with discharge (Figure 1). Riffles are commonly chosen as study sites because they are considered sensitive to flow and are important in terms of food production, fish passage, and spawning (Stalnaker *et al*, 1995; Anderson, 1998; Gippel and Stewardson, 1998). The basic premise of this method is that maximizing wetted perimeter per unit of discharge will protect the biological integrity of a riverine system.

Although the wetted perimeter method is fairly easy to calculate, it may fail to account for important habitat characteristics. For example, in wide, flat, uniform channels only a very shallow flow may be required to maintain water across the entire channel, yet water depth and velocity may be unsuitable for many species (Jowett, 1997). Inflection points are often chosen on a subjective basis and recommendations can vary between investigators, as there is no standardized method for selecting an inflection point and complications often

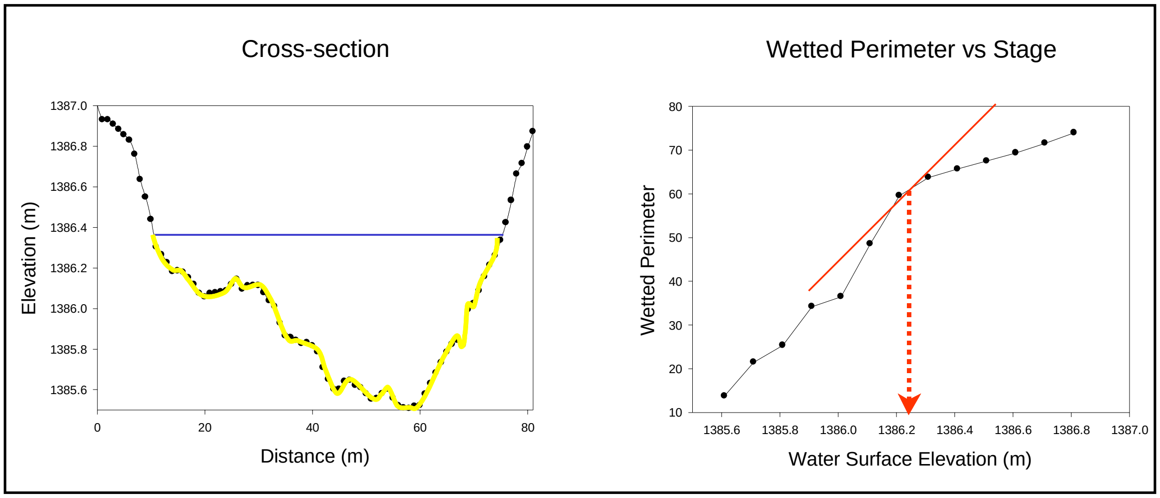


Figure 1: Conceptualization of the wetted perimeter method.

arise when there is no clearly defined breakpoint or when multiple inflection points are present (Annear and Conder, 1984). Another problem with the wetted perimeter method is that it only provides for minimum flow recommendations (Gippel and Stewardson, 1998). In recent years, it has been demonstrated that the magnitude, frequency, duration, timing, and the rate of change in flow are important components of river ecosystems (Poff *et al.*, 1997). Instream flow assessments need to account for temporal variability in flow and quantitatively assess the effects on habitat (Stalnaker *et al*, 1996). The end result is that although instream flow rights granted using the wetted perimeter methodology are likely to maintain the appearance of a river, they may fall far short of performing the river's ecological functions (Jowett, 1997).

The most widely used instream flow assessment tool in the United States is PHABSIM (Reiser *et al.*, 1989). This method relies on a variety of one-dimensional step-backwater hydraulic models that calculate depth and average velocity at cross-sections over a range of flows (Tarbet and Hardy, 1996). Velocities are distributed across the channel based on field measurements of the velocity distribution over some range of flows. PHABSIM delineates useable habitat based on evaluations of individual fish preferences for depth, velocity, and substrate/cover for a specific target species and life stage. Weighted useable area (WUA), a measure of habitat area based on depth and velocity preferences, represents microhabitat availability for a target species (Figure 2) (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).

PHABSIM has been criticized for both physical and biological reasons including: 1) the relationship between WUA and population response has never been established, 2) it focuses on single species and life stages, and 3) it uses a one-dimensional flow model which cannot accurately represent velocity distributions on streams with significant lateral flow components (Bovee, 1996a; Espegren, 1998; Mathur *et al*, 1985; Scott and Shirvell, 1987). PHABSIM relies on the assumption that habitat parameters can be modeled at a biologically significant level, as do almost all instream flow methodologies (Hardy, 1998). However, with a step-backwater model as used in PHABSIM it is difficult to obtain reliable results for areas less than 10 m^2, making habitat description difficult at a scale relevant to fish, which commonly occupy a space smaller than 1 m^2 (Leclerc *et al*, 1995).

Assessing the habitat requirements of fish in warmwater streams using PHABSIM can be especially problematic (Nestler, 1990). In warmwater 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). In warmwater systems, a broader community level perspective that simultaneously considers multiple species is probably required for examining the relationship between flow and habitat

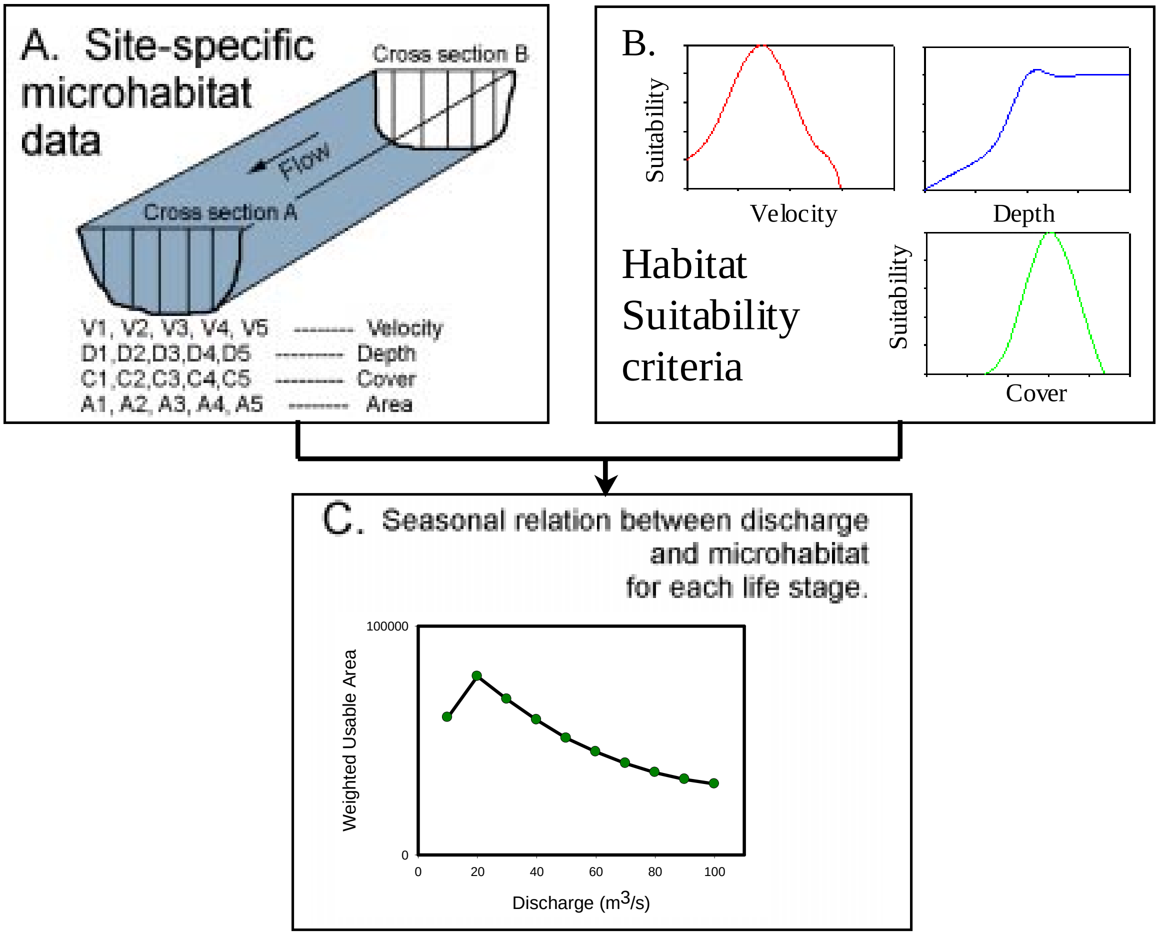


Figure 2: Conceptualization of how PHABSIM calculates habitat values as a function of discharge (adapted from Stalnaker et al., 1995)

because of the likelihood of differential responses of species to fluctuating streamflows (Lobb and Orth, 1991; Anderson, 1998). There have also been questions raised, in general, about whether measurements of microhabitat availability for specific species and life stages can be assumed to be positively related to biomass (Mathur *et al*, 1985). A predator may occupy habitat that is considered “optimal” habitat for one of its prey species. In such a case, maximum microhabitat availability for the prey species may not be positively correlated to biomass. In systems where fish diversity is high, and predator and prey species can be found in close proximity, the size, density, and connectivity of habitat patches may limit biomass. Finally, the need for a large number of accurate cross-sectional surveys may serve as a barrier to the use of PHABSIM in rivers that are too deep to wade (Ghanem *et al*., 1996).

A number of authors have suggested that two-dimensional flow models should offer significant improvement over one-dimensional modeling in determining habitat metrics as a function of flow (Leclerc *et al*., 1995; Bovee, 1996a; Ghanem *et al*., 1996; Hardy, 1998). Traditional instream flow methods can account for temporal variability, but are generally very poorly suited to the analysis of spatial metrics. Spatially explicit flow models 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 can be limiting to fish existence including habitat heterogeneity/diversity (Bovee, 1996a; Ghanem *et al*. 1996). Because two-dimensional model results are spatially explicit and can be mapped, they are ideally suited for computation of landscape ecology metrics across a variety of spatial scales including examination of habitat utilization and variability at the scale of a fish community (Bovee, 1996a; Hardy, 1998).

1.2 Significance

In 1973 the Colorado state legislature passed Senate Bill 97, which established the State’s instream flow program. The mission of the program was “...correlating the activities of mankind with some reasonable preservation of the natural environment." As part of their mission to protect the environment, the Colorado Water Conservation Board (CWCB) has been tasked with filing for instream flow rights. In order to make determinations of how much water should be left instream, the CWCB has asked the Colorado State Division of Wildlife (CDOW) to provide instream flow recommendations based on biological assessments and the availability of water.

The CWCB, in cooperation with the CDOW, developed a methodology based on the R2CROSS program (Nehring, 1979; Espegren, 1996). This methodology, like the inflection point method, is based on the assumption that riffles are the most critical habitat type. R2CROSS is a Lotus 1-2-3 spreadsheet-based macro that uses the Manning equation to determine average cross section depth, average cross section velocity, and percent wetted perimeter over a range of flows using single stream transects (Espegren, 1998). The hydraulic criteria that were developed for use with this model were specifically designed to protect the flow needs of coldwater fish species within riffle habitat (Nehring, 1979). It has been recognized by the CWCB, however, that more sophisticated models may be required on highly controversial stream segments and on streams with species other than trout (i.e., warmwater, coolwater, and endangered species) (Espegren, 1998).

In 1996, the Colorado Division of Wildlife participated in a Colorado River Recovery Program study to recommend minimum stream flow needs for Colorado pikeminnow (*Ptychocheilus lucius*) on the Yampa River and used the "inflection point" method. In the CDOW study a minimum flow recommendation of 2.63 cms (93 cfs) was based on an average of 32 riffle cross sections. In the study, the authors state that the 93 cfs flow recommended by the study was less than flow predicted by PHABSIM to maintain pool and run habitat availability for two endangered species on the river (Modde *et al.,* 1999). After an internal review, CWCB expressed a desire to have a more standardized approach for instream flow filings and the CDOW determined that two-dimensional modeling should be performed to provide further insight into the physical riverine processes that may be affecting the native fish community. Additionally, it was hoped that recommendations two-dimensional modeling results might support the continued use of the wetted perimeter method (R. Anderson pers. com., 1998).

1.3 Study Area

Two different river reaches were examined in this study. The original study plan called for three reaches to be modeled, two on the Yampa River and one on the Colorado River, but sufficient data were only available for one site on the Yampa and one on the Colorado. These sites were chosen because the CDOW was interested in making instream flow recommendations for these sites and because the sites exhibit significant differences in flow regime and species composition.

1.3.1 Yampa River – Duffy Tunnel

The Duffy Tunnel site is approximately 2.25 km long and is centered near River Mile (RM) 109.5, in the lower part of Little Yampa Canyon in western Colorado (Figure 3).

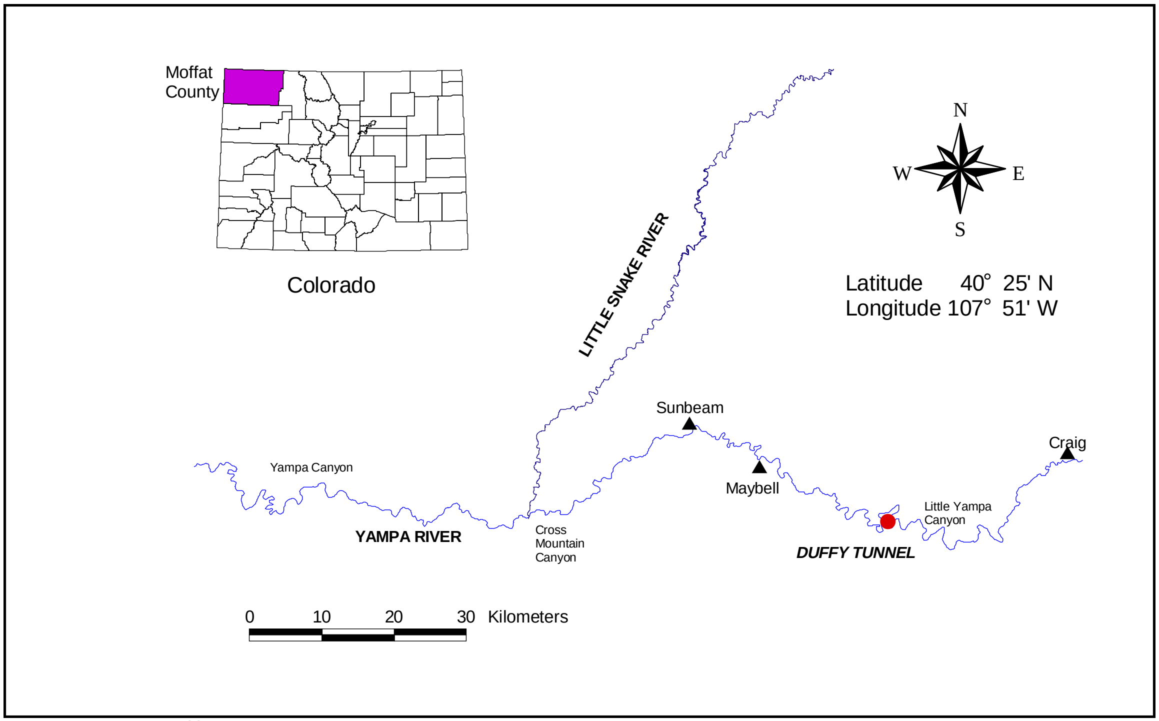


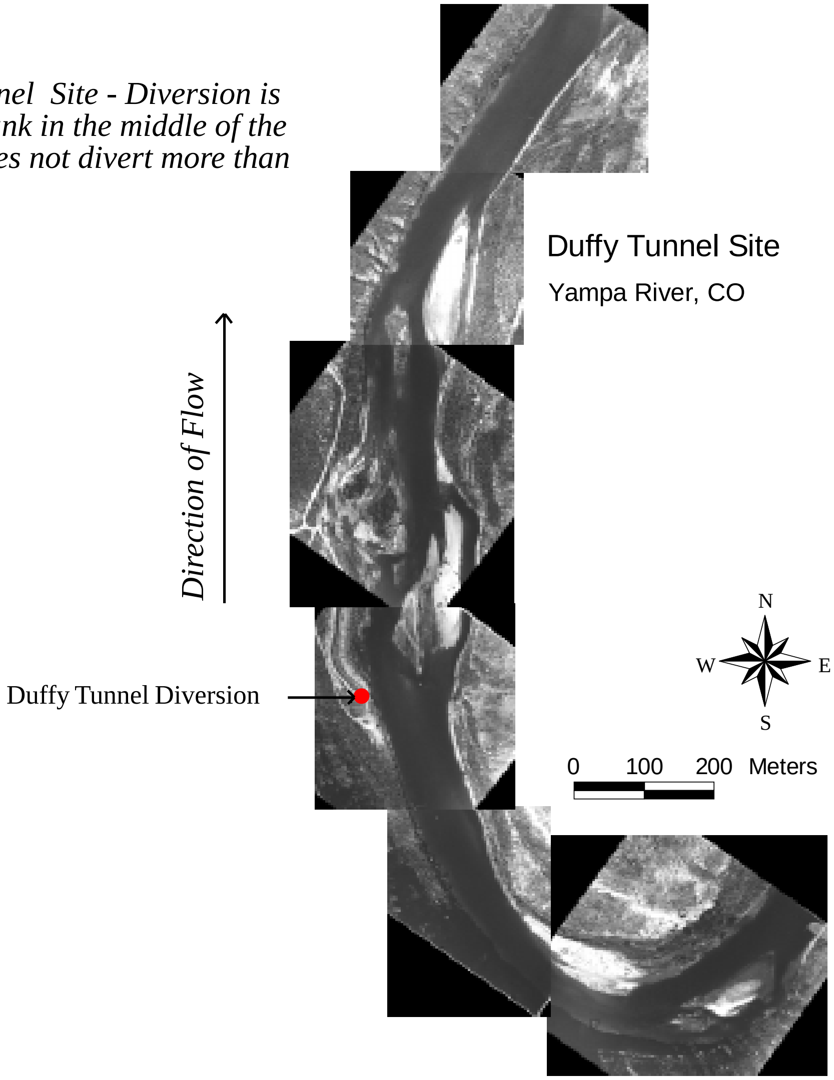
Figure 3: Duffy Tunnel study site on the Yampa River in western Colorado.

The river in this area flows through high desert terrain and the site is moderately confined within a large canyon. The gradient of the river in this section is approximately 0.1% and the bed material is commonly sand and gravel, with areas of small cobble. Channel morphology is generally riffle/run with 500-1000 meter long runs separated by 150-200 meter long riffles. In many places the river is in close proximity to the bedrock canyon wall and large boulders from the canyon wall have been deposited in the channel. The Duffy Tunnel site is named after the Duffy Tunnel diversion, located in the middle of the site. This diversion was built in the late 1900's and diverts a small but unknown quantity of water during the irrigation season (probably no more than 0.3 cms). A large number of boulders are located just downstream from the diversion structure and were presumably placed in the channel as part of the diversion works (Figure 4).

Adult fish (>15cm) compositions for the Duffy Tunnel reach were determined with electrofishing, and results show that approximately 10% of the eleven fish found in the study site are native species. Flannelmouth sucker (*Catostomus latipinnis*) composed only 2.4% of the fish caught, bluehead sucker (*Catostomus discobolus*) composed only 4.3%, and white sucker (*Catostomus commersoni*) and white sucker hybrids account for 77.8%. Non-native predators including northern pike (*Esox lucius*), channel catfish (*Ictarurus punctatus*), and smallmouth bass (*Mictropterus dolomieui*) comprised about 13% of the fish caught. The total fish density estimate made for an 8 kilometer section of the Yampa River that included the Duffy Tunnel reach is approximately 409 per kilometer (± 29, 95% CI) (Anderson and Stewart, 2000). It is assumed that the large boulders in the channel area may be important for providing instream cover for smallmouth bass, but not for native fish.

The Yampa River has no large mainstem dams so flows are largely unregulated with a significant spring peak dropping off to low summer baseflows (Figure 5). The spring peak has been relatively unaffected by development in the basin, whereas late summer baseflows have been significantly affected by agricultural withdrawals. According to Colorado River Decision Support System (CRDSS) models, the natural flow in the area of study was

Figure 4: Duffy Tunnel Site - Diversion is located on the left bank in the middle of the site and probably does not divert more than 10 cfs at any time.



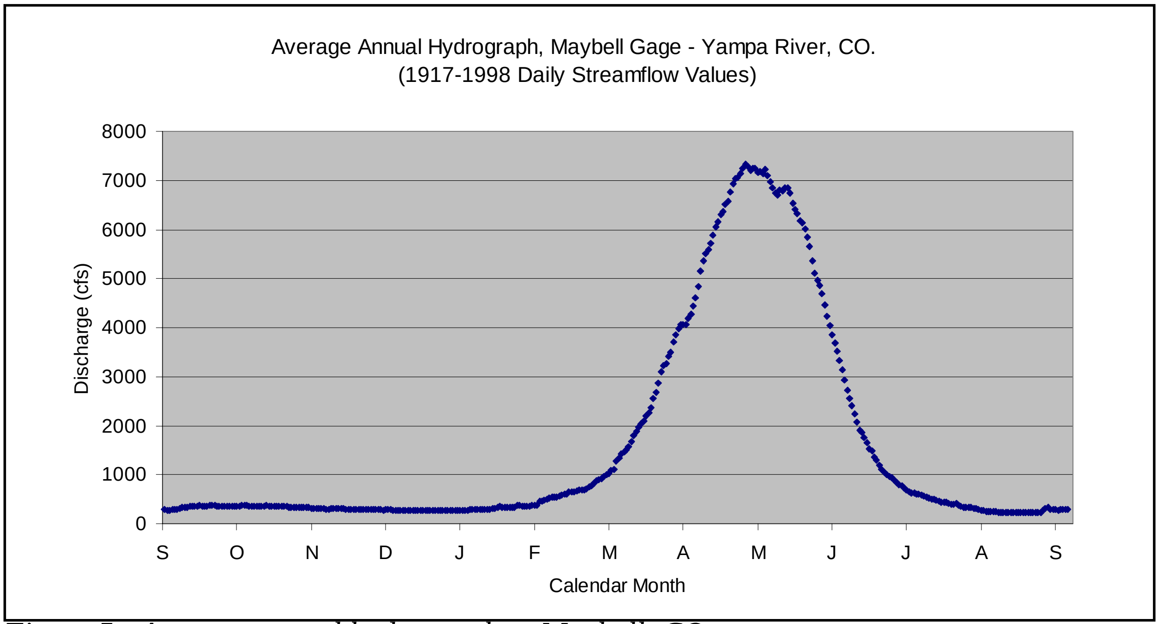


Figure 5: Average annual hydrograph at Maybell, CO

depleted by 50% or more during the months of August and September in 6 of the 17 years between 1975 and 1991. These depletions are associated with late season irrigation demands and depletions for those months averaged approximately 30% (Modde *et al*. 1999).

1.3.2 Colorado River – 15-Mile Reach

The 15-Mile reach of the Colorado River extends from Palisade, Colorado (RM 185) downstream to the confluence of the Gunnison River at about RM 170 (Figure 6). The study reach occupies a 4 km section located from RM 177.4, which is at the boat launch at Corn Lake, downstream to RM 174.9 (Figure 8). The river in this section has a gradient of 0.15% and is generally of a riffle/run morphology. The river flows through a wide valley, but is confined by levees in many places because of the proximity of urban development.

Percentages of adult fish (>15cm) caught by electrofishing show that only 82% of the fifteen fish in the 15-Mile reach are native and that flannelmouth sucker was the most abundant species at 41% and bluehead suckers comprised 38% of the sample. Catfish comprised only 5% of the fish caught in the study reach, and other non-native predators were rare. Fish density was almost 6.4 times higher for the 15-Mile reach study site than for the Yampa River site, with a total fish density estimate of 3,962 per km (± 435, 95% CI) (Anderson and Stewart, 2000).

The flow regime of the 15-Mile reach is significantly different from that of the Duffy Tunnel site (Figure 7). Although two major upstream diversions dewater the river in the 15-Mile reach during the irrigation season, low flows are generally not significantly altered during the remainder of the year. Winter (November to March) flows recorded in the 15-Mile reach appear to be equal to or higher than historic winter flows because the senior water right at the Shoshone Power Plant in Glenwood Canyon, located approximately 145 kilometers upstream, calls for water to be released from upstream reservoirs in the winter. The magnitude and duration of the spring runoff flows, however, have been significantly reduced by several upstream water projects that store water for delivery out of the basin.

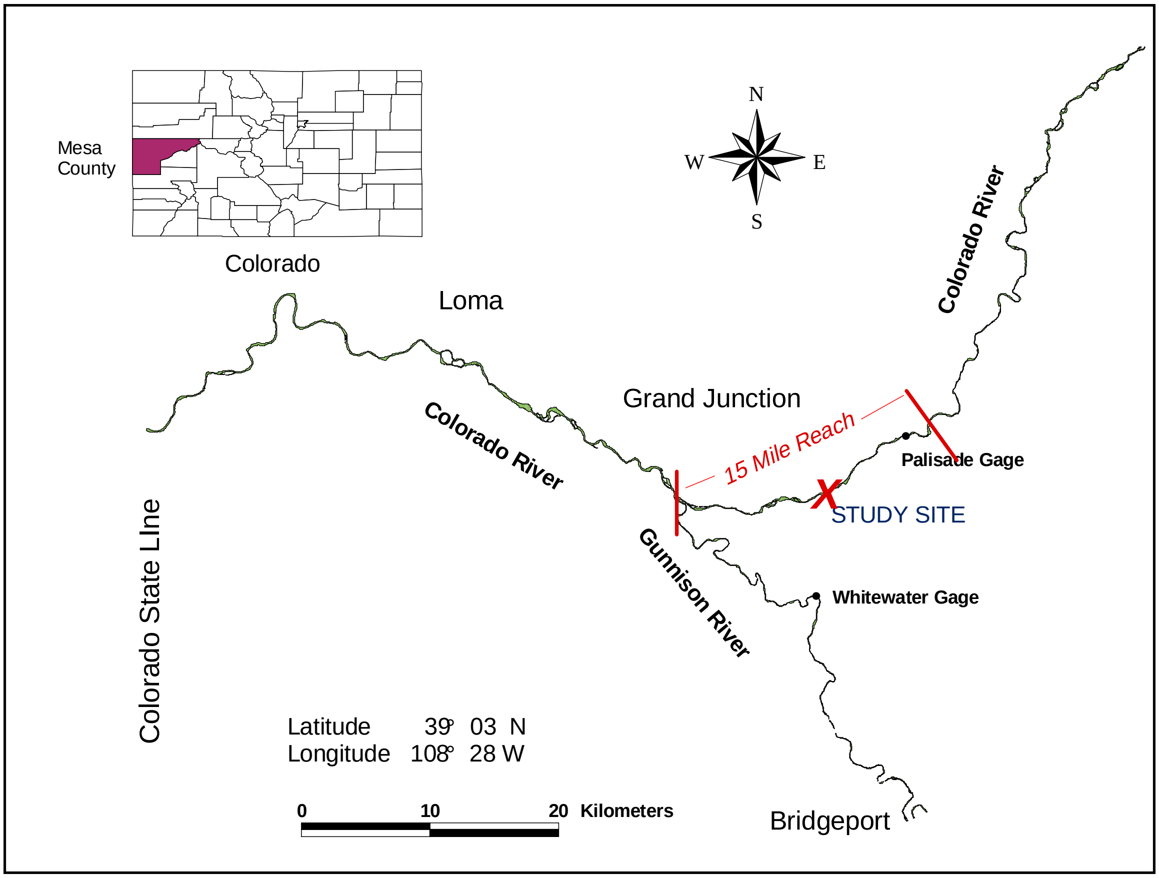


Figure 6: Study site on the 15 Mile Reach of the Colorado River.

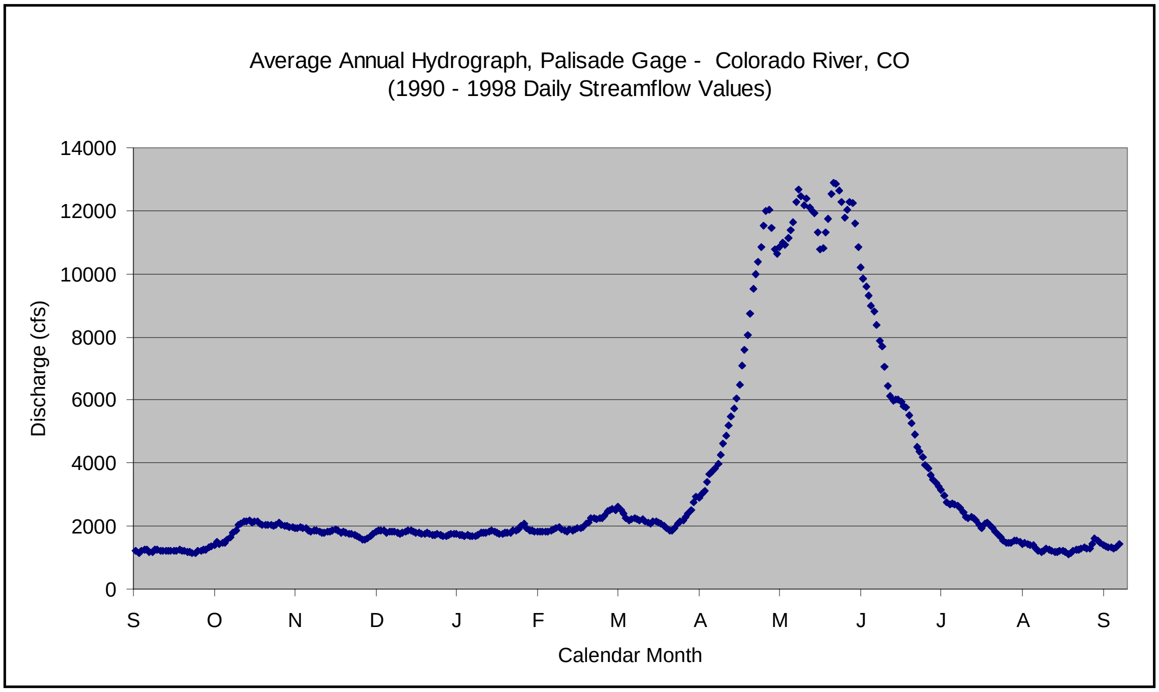


Figure 7: Average annual hydrograph at Palisade, CO

Figure 8: Study site on the 15 Mile Reach of the Colorado River near Palisade, CO.

For an average year, the peak flows during the runoff season are reduced by about 40% at the Cameo gage located approximately 10 km upstream from the 15-Mile reach (Anderson and Stewart, 2000).

1.4 Hypothesis

H1: Meso-habitat availability, expressed in terms of either total area or percent area, will be correlated with adult fish abundance (length >15 cm) expressed as a percentage of the fish caught in a sub-section of the modeling reach.

Meso-habitat is a channel scale habitat unit that includes riffles, runs, and pools. The idea is that fish will choose to be in a sub-reach where there is an abundance of suitable habitat. As the amount of suitable habitat increases, more fish will occupy the space. This hypothesis is similar to the argument that is made for maximizing weighted usable area in PHABSIM, except that the correlations in this study are based percentage of fish in the community and no *a priori* assumptions are made regarding habitat preferences. As such, habitat utilization is a factor of both biotic and abiotic processes acting at the community level.

H2: Plots of habitat diversity and wetted area against discharge will show that both decline with declining discharge.

As discharge decreases so should the wetted area of the channel, which is a plan view measurement of the area covered by water. Furthermore, as the wetted area decreases, habitat diversity should decrease to the point that only a few habitat types are present.

H3: Plots of wetted area vs. discharge will be similar to those found in the 1996 CDOW study and will feature an inflection point somewhere near 93 cfs.

The rate that wetted area decreases with discharge is probably similar to that for wetted perimeter. If so, it is reasonable to suspect that the inflection point on plot of wetted area vs. discharge would occur at approximately the same discharge as on a plot of wetted perimeter vs. discharge.

H4: Plots of habitat diversity vs. discharge will, however, show that habitat diversity is maximized as a function of discharge at significantly higher flows than 93 cfs at the Duffy Tunnel site.

While habitat diversity and wetted area are both expected to decrease with discharge, it is expected that habitat diversity will decrease more rapidly than wetted perimeter, or wetted area. For example, on a wide very shallow river one might expect habitat diversity to be very low even though wetted area is still relatively large.

1.5 Objectives

The objectives of this study are:

1) to use the RMA2 hydraulic simulation model to evaluate how depth and velocity change over twelve different discharges on two warmwater river reaches in western Colorado, one on the Colorado River and one on the Yampa River,
2) to generate 1x1 meter grid-based meso-habitat maps for each of the twelve flows at each of the study areas, using two-dimensional depth and velocity calculations from RMA2 and meso-habitat definitions provided by the Colorado Division of Wildlife for the purpose of this study,
3) to use the meso-habitat maps to evaluate ecological metrics of habitat including habitat diversity and richness using the Fragstats spatial pattern analysis program for quantifying landscape structure,
4) to create plots of meso-habitat diversity, richness, and wetted area against discharge for comparison against previously used instream flow methods and for use in making instream flow recommendations on the two study rivers, and
5) to provide an evaluation of the use of two-dimensional modeling for making instream flow recommendations to the Colorado Division of Wildlife for the purpose of guiding their instream flow program.

Chapter II - METHODS

2.1 Equipment

In order to accurately represent the flow characteristics of a river reach using two-dimensional hydraulic models, a large data set is required including topography/bathymetry of the reach to be modeled and measurements of velocity, depth, and/or water surface elevation for use in model calibration. The collection of these data is very time consuming and may represent a large proportion of the total project cost. There are several ways in which topographic data can be collected, and two different methods were used in this study (total station and GPS/sonar). Calibration information was also collected by two different methods in this study (Marsh-McBirney and acoustic Doppler current profiler (ADP)).

2.1.1 Total Station

In 1998, river topography was surveyed at two locations on the Yampa River using a Pentax PTSIII total station. A total station allows the user to select only those survey points that are necessary to represent the topography and to gather data only at those points. Total stations calculate positions using basic trigonometric relationships. The total station uses a laser beam to determine the distance to a survey prism while simultaneously measuring the horizontal and vertical angles to the prism. Machine accuracy is generally represented by the precision to which angles and distances can be measured. With a horizontal and vertical accuracy of 3 arc seconds, the relative horizontal and vertical error is 1.45E-5 of the measurement distance. Because an effort was made in this project not to shoot points at a distance of more than 300 m from the total station, the amount of error introduced by machine precision was limited to less than +/- 4mm in any dimension.

2.1.2 Global Positioning Systems and Sonar

In 1999, Global Positioning Systems (GPS) and sonar technology were used to gather bathymetric surveys of the channel (Figure 9). This technique allowed the collection of a large amount of data in a short amount of time. Although there have been advances in GPS technology, the basic concept of GPS remains the same. GPS satellites with known orbits broadcast pseudo random code synchronized to universal time. A GPS receiver receives the signal from at least four satellites and calculates a distance to the satellites based on the amount of time required for the signal to reach it. Using trigonometry, it is possible for the receiver to calculate its position in space if it knows the distance to four known points.

When calculating a GPS position, vertical distance is the hardest to accurately calculate because of the relative position of the satellites, errors introduced by the atmosphere, and the method by which the receiver calculates distance. Because the errors in bathymetry mapped by GPS and sonar represent the sum of the errors in the sonar and GPS data, it is very important to use a high quality GPS system. The GPS system used in this study was a Javad Odyssey L1/L2 RTK GPS with Glonass and Multi-path reduction options turned on. This system has a published vertical accuracy of 15mm +/- 1.5 mm per kilometer of distance between the base station and rover GPS units. As a quick test of the accuracy of the system in the field, a single point was surveyed repeatedly at a rate of about once per minute for 20 minutes. The point was located approximately 1 km from the base station and the standard deviation of the elevations was 0.002 meters.

The sonar unit used was an ODOM Hydrographic Systems, Hydrotrac - Single Frequency, Portable Survey Sounder. This unit used a 200kHZ frequency with a published accuracy of 1cm +/- 1% of depth and an output resolution of 1cm. Although no detailed study was made to verify the accuracy of the sonar unit because of time constraints and the difficulty of making such determinations in a river system, it was possible to visually verify that the readings did not vary by more than 1cm while covering plainbed river features.

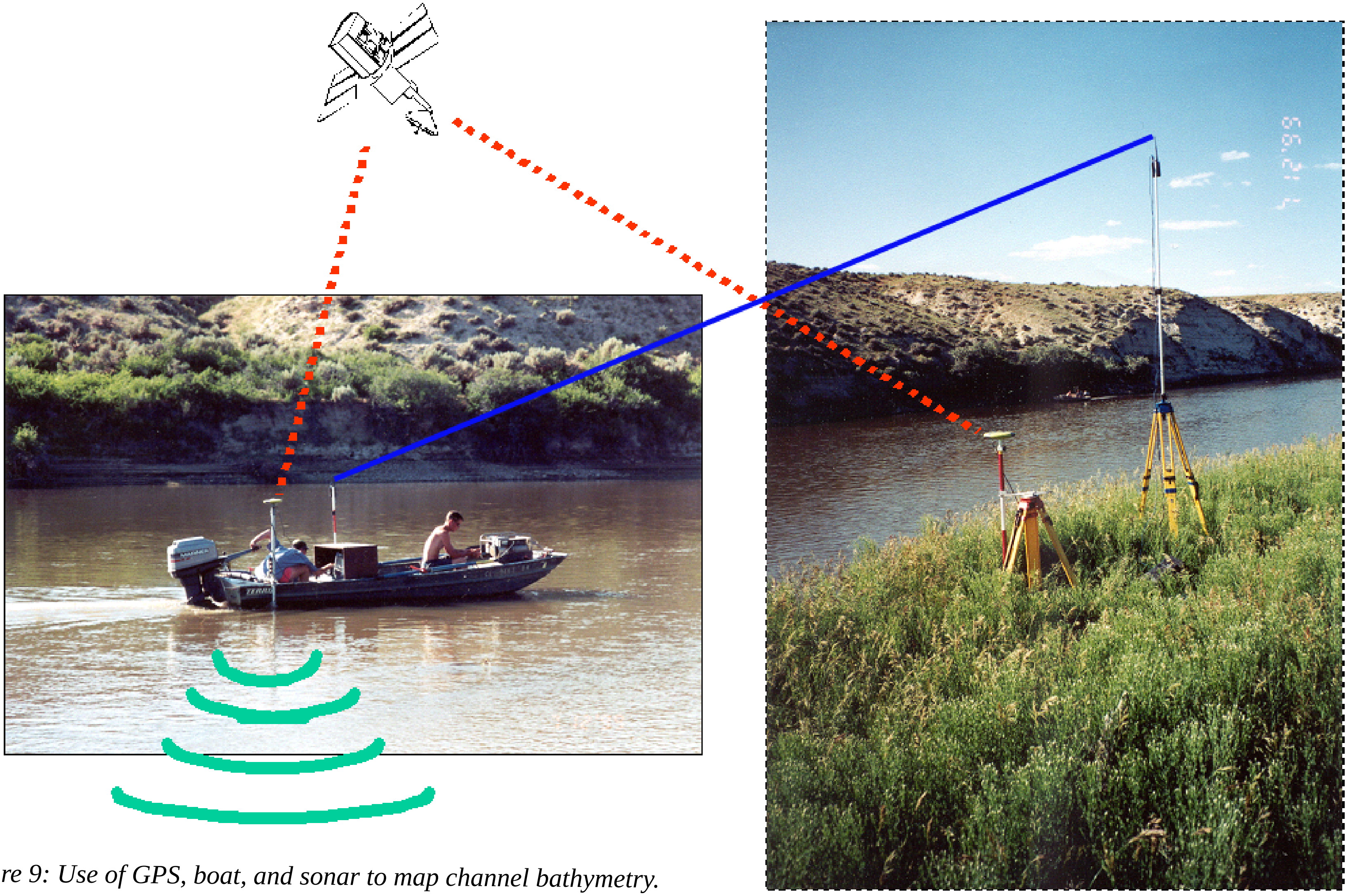


Figure 9: Use of GPS, boat, and sonar to map channel bathymetry.

Two GPS receivers are used to obtain satellite locations and the base receiver on land sends real time error correction to the rover receiver based on the difference between the computed and known location of the base station.

One of the greatest hindrances to using sonar to map the channel bottom is that sonar has a minimum depth requirement. In order for the sonar to get a reading off the bottom of the channel, the transducer used in this study required at least half a meter of water underneath it. For this study, the transducer was located approximately 15cm below the water surface, which provided some tolerance for the pitch and roll of the boat and minimized air entrainment. These constraints, however, made it difficult to gather bathymetric data in areas shallower than 75cm.

2.1.3 Marsh McBirney Electromagnetic current measurement

In 1998, a Marsh McBirney Flo-Mate Portable Flowmeter was used in conjunction with the total station to determine point velocities. The Marsh McBirney has a published accuracy of 1.5cm/s +/- 2% of reading and is based on the electrical principle known as Farraday's Law, where the flow rate of the fluid can be determined by passing a conductive fluid through a magnetic field. A wading rod was used to hold the meter head at a depth chosen to represent average velocity (0.6 of total depth in this study). Locations were surveyed with the total station and velocities were recorded based on the average of three 10-second averages. Because depth was required for model calibration, water surface elevations were recorded on the bank closest to where the velocity measurements were taken. Depths were then determined by subtracting the water surface elevation from the river bottom elevation at each of the velocity measurement points.

2.1.4 Acoustic Doppler Current Profiler

In larger rivers with high velocities and deep areas, it is often impractical to use a wading rod and current meter to measure velocities. In May of 2000, a 3MHZ Sontek River Surveyor Acoustic Doppler Profiler was purchased by the Colorado Division of Wildlife for the purpose of gathering calibration data on the 15-Mile reach of the Colorado River. An ADP measures the velocity of water using a physical principle called the Doppler shift. This states that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency. By determining the Doppler shift of the water relative to the bottom, it is possible to determine the speed and direction of the flow. The ADP measures velocities in 15cm vertical increments down to the river bottom. These velocities are averaged over a specified time interval resulting in an average velocity for the given point.

2.2 Data Collection

Most of the field data were collected during the summers of 1998 and 1999. In 1998, the total station and flowmeter were used to gather data on two reaches of the Yampa River. Data collected in 1998 were never modeled because critical data were lacking from the surveys. In 1999, both sites on the Yampa River were re-surveyed using the GPS/sonar, and an additional site was surveyed on the 15-Mile reach of the Colorado River. Only one site on the Yampa River was modeled because critical data related to the second site were lost during an equipment failure near the end of 1999.

Data collected in 1998 were used to calibrate the Duffy Tunnel model, and ADP collected in late April, 2000 were used for calibration of the 15 Mile reach.

2.2.1 1998 Duffy Tunnel and Sevens Surveys

During the months of July and August of 1998, a Pentax PTSIII total station was used to obtain XYZ coordinates for two reaches on the Yampa River. The first reach, designated Duffy Tunnel, was located approximately 24 kilometers upstream from Juniper Hotsprings near the Duffy Tunnel diversion. This survey site was approximately 1.3 km long and 3777 data points were collected. The second site, designated Sevens, was located adjacent to Cross Mountain Ranch approximately 8 kilometers upstream from Cross Mountain Canyon. This survey site was approximately 1.2 km long and was represented by 1900 data points.

To make sure that the data collected at each of the sites could be used in future research, a conscious effort was made to tie the surveys into permanent benchmarks. In order to place the surveys into a real world reference system, a Trimble GeoExplorer II GPS was used to record the locations of at least two benchmarks for each site. The BLM in Craig, CO maintains a base station that was used to post-process and differentially correct the GPS data. By letting the GPS average the position for each point for 10 minutes and then post-processing, it was possible to determine the positions of the benchmarks to within approximately 10cm. These positions were then converted into the State Plane 1983 coordinate system using the NAD83 datum and the Colorado North zone. The State Plane coordinate system was chosen for the 1998 surveys because it was the coordinate system of choice for the CDOW and is based on the English system of units. At each site, one ground control point (GCP) was selected to be the reference position and other GCP's were used for determining azimuth and as a rough check on total station coordinates.

Bed elevations were surveyed during the low flow periods by walking, wading, or floating the channel with a collapsible rod and prism and shooting the position with the total station. Points were captured at breaks in slope rather than on transects. Where channel topography varied, a greater density of points was captured compared to areas with relatively planar surfaces. Substrate was determined visually on dry land and on shallow riffles and by tapping with the rod where the water was too deep to wade. Channel substrate, feature, and habitat type were recorded for each XYZ data point. An effort was made not to shoot any points at a distance of over 300m to reduce the amount of measurement error. Velocities were determined by surveying a point with the total station and then placing the Marsh McBirney Flowmeter in that location for 30 seconds.

Both of the 1998 surveys started and/or ended on riffles with multiple channels. Because no data were collected relating to the distribution of flow among the inflow channels, it was impossible to accurately model the reach using just the 1998 data.

2.2.2 1999 15-Mile Reach Survey

During a seven-day period in June and July, a GPS and sonar system was used to collect bathymetric points on a 4 km stretch of the 15-Mile reach of the Colorado River between river miles 174.8 and 177.4. During this period, 38,880 usable bathymetric survey points were collected.

The 15-Mile reach survey was tied into the Mesa County Survey System. The Mesa County Dept. of Public Works Engineering Division/Survey Section maintains a web page showing the locations of the county markers. The latitude and longitude of the brass marker at the intersection of 31 and C Road were determined through the use of this website. Using the brass marker reference point, it was possible to use the Javad RTK GPS to pinpoint the location of a rebar pin near river mile 175. This point was subsequently used as the reference point for the entire 15-Mile reach survey.

Bathymetric survey data were collected from a 4.5 meter long flat-bottom boat using the Javad RTK GPS and ODOM Hydrographic 3000HZ narrow beam sonar. The GPS system transmits a NMEA GGA string at a rate of 1HZ whereas the sonar transmits depth measurements at a rate of 10HZ. Data from these instruments were sent to a laptop and recorded using the COMLOG software from ODOM Hydrographic. Because the GPS and sonar data were received at different rates, all data entries collected by the COMLOG software were time-tagged to the millisecond using the computer’s clock.

Data were collected from longitudinal runs and cross-sectional surveys. Special care was taken to ensure that the transducer and GPS antenna were mounted in such a way as to remain nearly vertical during each run. On October 1999, additional topographic points were collected at the waterline with the GPS, Psion data collector, and Field Face software. These additional points were used for calibrating the Manning roughness values in the one-dimensional step-backwater model (see section 2.5).

During the first week of April 2000, calibration data were collected on the 15-Mile reach using the ADP. These data were collected as the river was rising and data on two different flows were collected and were not in cross-sectional form. The ADP software was configured to continuously record 30-second averages of depth and velocity. The boat on which the ADP was mounted moved to a point of interest, maintained station for 30 seconds, and then moved on to the next point of interest. During post-processing of the data, the distance the boat moved during a given 30-second period was calculated using both the ADP bottom track and the GPS. If the calculated boat movement exceeded 3 meters during a given 30-second period, that point was dropped.

2.2.3 1999 Duffy Tunnel Survey

Over a three-day period in July 1999, bathymetric data were collected along a 2.25 km section of the Yampa River near Duffy Tunnel. In order to compare the 1998 and 1999 data sets, the 1999 survey used the coordinates of the primary base pin of the 1998 survey. Bathymetric data were collected on this reach of river using the same method as used on the 15-Mile reach (Sec. 2.2.2). However, because flows were relatively low it was not possible to survey the margins of the channel using GPS and sonar. As such, from 27 through 29 July, the GPS was used with a Psion data collector running Field Face software to survey the waterline.

2.3 Use of 1998 Survey Data in Duffy Tunnel Model

Bathymetric data collected in 1998 were used to create the Duffy Tunnel SMS model because the 1999 bathymetric survey was conducted during relatively low flows and it was not possible to accurately represent the large number of boulders or channel complexity around the Duffy Tunnel diversion. Careful consideration was given as to whether the bed had changed significantly between 1998 and 1999. Such changes would make the 1998 and 1999 data incompatible.

To determine whether bed topography had changed significantly, both surveys were examined and 36 points were chosen from each survey. The points that were chosen were spatially distributed and existed in relatively the same location in both surveys. Using the identify tool in ArcView, elevations for selected points were identified and then manually entered into an Excel spreadsheet. The choice of 36 points was made out of convenience and not for any statistical or other reason. A comparison of the elevations found that the average absolute error was 3.3 cm +/- 3.5 cm (95% CI) with the largest errors resulting from the points with the greatest lateral offset.

Because of the difficulty associated with finding identically positioned points in the two surveys, two methods were used to look for patterns of bed change. Both methods involved interpolating channel surfaces from the survey data and subtracting one surface from the other. Both the interpolation methods failed to show any pattern of channel change. Therefore, based on the visual sampling of 36 points and the lack of any pattern of channel change, the surveys were considered to be reasonably compatible and the 1998 survey was combined with the 1999 survey for the purpose of delineating the Duffy Tunnel mesh elevations.

2.4 Data Reduction and Preparation

Each of the survey methodologies used required that data be collected over an extended period, and in each survey methodology a large number of data were collected. Because of this, quality control was a very important part of the survey process. Data from individual surveys had to be joined together in a seamless manner and an effort had to be made to determine when a sufficient amount of data had been collected. The combined use of GPS and sonar to collect data added an additional set of issues because it was generally not possible to perform any quality control as the data were being collected.

Using the total station, it was possible to limit data collection to areas where additional surveys would help define the channel topography. As topographic data were collected over the summer, they were input into the ArcView software package. This software made it possible to create a Triangular Irregular Network (TIN) surface model of the channel. By mapping the topographic points on the TIN, it was possible to determine where additional survey points were needed in order to accurately represent channel topography.

The use of GPS, sonar, and the COMLOG program resulted in a large amount of data that had to be reduced during post-processing. As part of this data reduction, an Excel macro was written to determine which points would be used as part of the final survey. First, the macro examined the GPS signals and eliminated all the ones that were not considered to be real time kinematic (RTK), based on the GPS data quality indicator in the NMEA data string. Then, because data were being collected from the sonar at such a high rate, and sonar readings were sometimes affected by fish or suspended material, spikes in the sonar data were eliminated based on the running average of the 3 sonar pings prior to and after a given sonar ping. If the elevation recorded in a given reading was different than the moving average of the 6 readings surrounding the given reading by more than 15cm, that ping was marked as “bad”. If an RTK GPS reading had a “bad” sonar ping recorded directly before or after it, that GPS reading was ignored. For those RTK GPS signals with “good” sonar recordings before and after them, the depth for that GPS position was determined through a linear interpolation of the sonar data based on the time tags. The elevation of the bed was calculated by subtracting sonar depth from the GPS elevations.

2.5 Preliminary Modeling

The two-dimensional model RMA2 will crash if the calculated water surface elevation drops below the bed elevation for any node along any inflow or outflow boundary. 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. 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 for the channel.

HEC-RAS is a one-dimensional hydraulic flow model created by the Hydrologic

Engineering Center of the U.S. Army Corps of Engineers (Bruner, 1998). HEC-RAS was designed to calculate water surface profiles for steady gradually varied flow based on solution of the one-dimensional energy equation (2.1 and 2.2).

$$Y_2 + Z_2 + \frac{\alpha_2 V_2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1}{2g} + h_e \cdots\cdots\cdots\cdots \text{(2.1)}$$

where $Y_{1,} Y_2$ = depth of water at cross sections
Z_1, Z_2 = bed elevation at cross sections
$V_{1,} V_2$ = average velocities (total discharge/total flow area)
a_1, a_2 = velocity weighting coefficients
g = gravitational acceleration
h_e = energy head loss

$$h_e = L\overline{S}_f + C\left|\frac{\alpha_2 V_2^{\,2}}{2g} - \frac{\alpha_1 V_1^{\,2}}{2g}\right| \cdots\cdots\cdots\cdots \text{(2.2)}$$

where L = discharge weighted reach length
S_f = representative friction slope between two cross sections
C = expansion or contraction loss coefficient

The model computes surface profiles from one cross section to the next by solving the energy equation with an iterative procedure called the standard step method. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regime water surface profiles. HEC-RAS has a graphical user interface (GUI) and requires station and elevation coordinates for each cross section. Energy loss because of friction is accounted for with cross-section average values for Manning n. Contraction and expansion of the channel is accounted with the inclusion of the distance between right, left and thalweg points at adjacent cross sections. Simulation output can be expressed in tabular or graphical format and generally consists of depth and average cross-sectional velocity (Bruner, 1998).

Because cross-sections were not specifically surveyed in the field, HEC-RAS cross-sections were created based on a triangulated irregular network (TIN) of the channel. Bathymetric data were imported into ArcInfo to create a TIN of the channel. This TIN was then opened in ArcView and a series of cross-sectional lines were created for use in HEC-RAS modeling. These line coverages were then exported back to ArcInfo and elevations were interpolated from the TIN at 1-meter intervals along the lines. For the 15-Mile reach, 32 cross-sections were created at approximately 100-meter intervals. For the Duffy Tunnel reach, a total of 46 cross-sections were interpolated off the TIN.

Data collected from the TIN, including the artificial channels, were subsequently entered into HEC-RAS. By creating additional rectangular cross-sections downstream from the outflow boundary of the 2-D model, it is possible to let HEC-RAS determine normal depth at the outflow boundary for any given discharge. Using the water surface elevations from HEC-RAS, a TIN was created representing the water surface elevation. By subtracting the bathymetry TIN from the water surface elevation TIN, it was possible to delineate the aerial wetted perimeter for the channel. This line was then used to bound the 2-D mesh.

There is one user-defined parameter in the HEC-RAS model that can affect the water surface elevations and that is the Manning n. Manning's n is an empirically derived number that represents the roughness of the bed in the Manning equation.

$$V = \frac{1}{n} R^{2/3} S^{1/2} \qquad \text{………………………………………(2.3)}$$

where V = velocity

n = roughness coeficient or “Manning's n”

R = hydraulic radius

S = slope

As Manning n increases, the velocity generally slows and the hydraulic radius increases. In channels with large width to depth ratios, like Duffy Tunnel and the 15 Mile Reach, depth and hydraulic radius are almost equal and can be used to approximate the average depth of the river. By calibrating the water surface elevation in HEC-RAS to measured water surface elevations at a given discharge, it was possible to determine an average Manning n for the channel.

2.6 Two-dimensional Modeling using SMS and RMA2

SMS is the Surface-Water Modeling System, a graphical user interface (GUI) used to create files for a number of computational fluid dynamic models including RMA2, FESWMS, and HIVEL2D. SMS was developed at Brigham Young University's Environmental Modeling Research Laboratory and is distributed through Environmental Modeling Systems, Inc. (EMS-I).

SMS gives the user a set of graphical tools to build files used by the modeling software and to graphically display the results of the modeling effort. SMS creates setup files for the different models. These files include the finite element mesh and a boundary condition file. Creation of input files with SMS is a time-consuming procedure but is of the greatest importance to a successful modeling in RMA2.

2.6.1 RMA2

RMA2 is a two-dimensional 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 two-dimensional flow fields using a finite element solution of the Reynolds form of the Navier Stokes equations for turbulent flows. The forms of the depth-integrated equations of fluid mass and momentum conservation in two directions are shown below.

$$h\frac{\partial u}{\partial t} + hu\frac{\partial u}{\partial x} + hv\frac{\partial u}{\partial y} - \frac{h}{\rho}(E_{xx}\frac{\partial^2 u}{\partial x^2} + Exy\frac{\partial^2}{\partial y})$$

$$+ gh(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x}) + \frac{gun^2}{(1.486h^{1/6})^2} + (u^2 + v^2)^{1/2}$$

$$-\zeta V_a{}^2\cos\psi + 2h\omega v\sin\phi = 0 \tag{2.4}$$

$$h\frac{\partial v}{\partial t} + hu\frac{\partial v}{\partial x} + hv\frac{\partial v}{\partial y} - \frac{h}{p}(E_{yx}\frac{\partial^2 v}{\partial x^2} + E_{yy}\frac{\partial^2 v}{\partial y^2})$$

$$+ gh(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y}) + \frac{gvn^2}{(1.486h^{1/6})^2} + (u^2 + v^2)^{1/2}$$

$$-\zeta V_a{}^2\sin\psi + 2h\omega v\sin\phi = 0 \tag{2.5}$$

$$\frac{\partial h}{\partial t} + h(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}) + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0 \tag{2.6}$$

where h = depth

u,v = velocities in Cartesian directions

x,y,t = Cartesian coordinates and time

r = density of fluid

E = eddy viscosity coefficient

for xx = normal direction on x axis surface

for yy = normal direction on y axis surface

for xy and yx = shear direction on each surface

g = acceleration due to gravity

a = elevation at bottom

n = Mannings roughness coefficient

Equations 2.4, 2.5, and 2.6 are solved by the finite element method using the Galerkin Method of weighted residuals. Integration in space is performed by Gaussian integration and derivatives in time are replaced by a non-linear finite difference approximation. Solutions are fully implicit and the set of simultaneous equations is solved by Newton-Raphson non linear iteration. RMA2 permits wetting and drying within the grid either through elemental elimination or gradual wetting and drying through the consideration of marsh porosity. Elements may be two dimensional quadrilaterals or triangles and may have curved sides (King, 1997).

2.6.2 Creating input files for RMA2 using the SMS interface

The SMS program has three modules that are used to create files for the modeling process: 1) mesh, 2) map, and 3) scatter. The mesh module is the primary module and is used for such things as editing the finite element mesh. The map module is used to import observation data and to create map files for use in automating the mesh creation process. The scatter point module is generally used for storing the topographic data.

The first step in modeling using SMS is to get the topographic data into the program and to begin the mesh creation process. SMS can import space delimited XYZ files containing the coordinates of the topographic survey. These coordinates should be in a single system of measurement, whether English or metric. Once the data are imported, the points can be triangulated and their elevations stored as a scatter point set in the scatter point module. Data stored as a scatter point set will be used for populating the mesh elevations.

The map module can then be used to start the mesh creation process. By importing the outlines of the wetted channel from waterline surveys, aerial photographs, and 1-D model results, the user can see where mesh boundaries should be drawn. Using drawing tools in the map module, arcs can be drawn to show this channel outline. Additional arcs can be drawn to break the channel into subunits based on material type or by flow characteristics. These arcs are then converted to polygons and the nodes are distributed along the edge of each polygon. By creating a connected set of lines to each node of a polygon, a mesh can be created.

There are two types of element that can be created from a map file. A triangular element can be created though adaptive tessellation or rectangular elements can be created using the patching option. The use of either element type is supported by RMA2 and both element types are useful. Where flow boundaries are relatively uniform, rectangular elements reduce the total number of elements needed in the model. This can be very useful when modeling a large spatial domain. Additionally, by creating long narrow rectangular elements along the channel margins, the process of turning elements on and off, to simulate wetting and drying, becomes more stable. Narrow elements placed along the banks represent smaller obstructions to flow as elements are turned off during the drying process. Triangular elements are necessary in areas where flow boundaries do not allow four sided rectangular elements, as shown in Figure 10. It could theoretically take twice the number of elements to populate an area using triangles, and creating thin triangles in areas of wetting and drying can be problematic. As such, for this project, it was determined that rectangular elements would be used where possible, though some areas such as eddies would be represented with triangulated elements for increased resolution.

Once the scatter points containing bathymetry have been created and the map polygons have been built and had the nodes distributed along their boundaries, SMS can be used

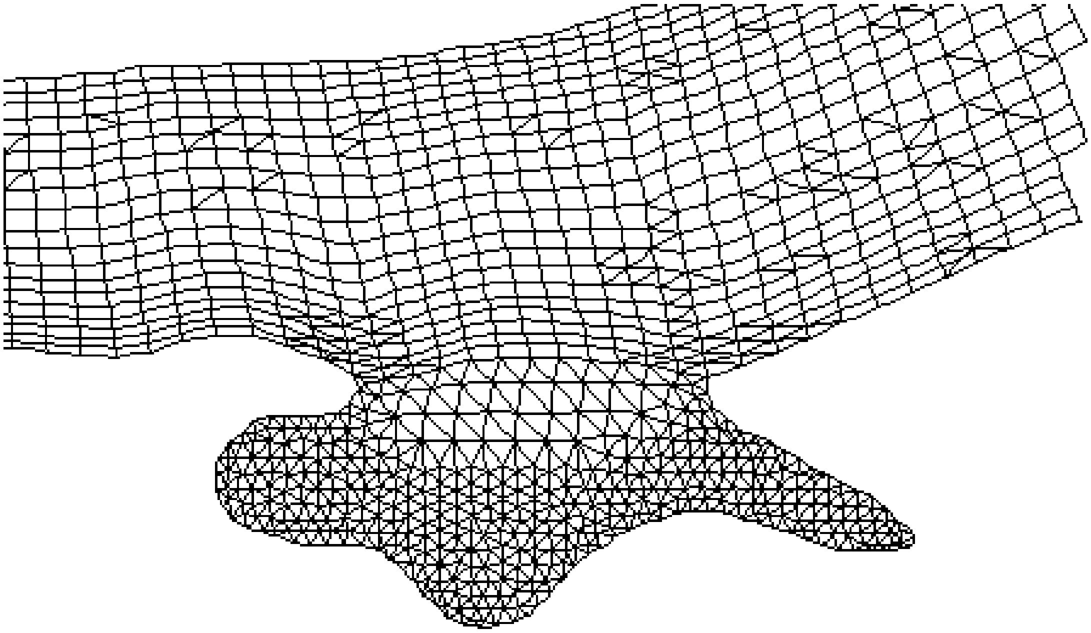


Figure 10: Example of element types, rectangular elements in main channel and triangular elements in the side channel area.

to create a finite element mesh for use in modeling. Although using the map module to create the mesh does save a large amount of work for the modeler, it is important to examine several mesh quality indicators and to make adjustments to the mesh based on expectations of the flow characteristics over the range of flows to be modeled. SMS has an option that allows the user to display elements that may have mesh quality problems. Using this option, the following six parameters can be evaluated; minimum interior angle, ambiguous gradient, concave quadrilaterals, maximum slope, element area change, connecting elements. Although no hard rules exist regarding limits for these parameters, SMS does provide some general guidelines.

Once a mesh has been created, material properties and boundary conditions can be assigned to elements using the boundary condition (BC) file. RMA2 allows the user to assign eddy viscosity and roughness coefficients elements by material type. This is a very useful feature, although it should be used with caution. It is not advisable to have a large number of material types unless there are sufficient field data to support the need for those types. Boundaries between materials types, where values for roughness can change significantly from one element to the next, can be sources of instability for the model and may make the calibration process more difficult. RMA2 does allow the user to set the roughness coefficient and eddy viscosity separately for each node, but this method for assigning values is generally not practical.

Boundary conditions are set once the mesh has been created, and evaluated, and material properties have been assigned. In RMA2, a water surface elevation is specified for the outflow boundary and discharge to the model is specified at inflow boundaries. These values can be specified for individual nodes, or along nodal strings that assign a set value to all nodes in the string. As stated in section 2.3, one problem with RMA2 is that if a boundary condition node goes dry during the simulation, the simulation will fail. Although there may be several ways to get around this problem, perhaps the simplest is to create artificial rectangular channels at the inflow and outflow boundaries. Because there is almost no change in wetted perimeter with discharge for a rectangular channel, this configuration is generally stable for all discharges.

2.6.3 Running an RMA2 model using SMS

Once a mesh has been created, and assigned material properties and boundary conditions, it is possible to run the model for the purpose of obtaining results. RMA2 simulations can be run as either steady state or dynamic simulations. 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 more appropriate to model steady state conditions.

RMA2 simulations are started using a downstream water surface elevation that is higher than the highest node in the model. The iteration method used in RMA2 requires initial guesses for the equations it will be solving. For the initial cold start run, RMA2 begins with a global, flat, water surface elevation as specified by the downstream boundary. 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 can be stepped down to the known downstream water surface elevation.

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, it is very important to step the model down slowly or the solution will diverge. Although it is easy to create small incremental steps with which to lower the outflow boundary, the stepping down process may still be very difficult because of wetting and drying. The reduction in flow area caused by an element being turned off during the wetting and drying process can change flow characteristics and cause the model to become unstable. For this reason, model runs for this project tended to follow a sequence as shown in the flow chart in Figure 11. This sequence is followed until the model reaches the boundary conditions of interest. Once the boundary conditions of interest have been reached, elements that have been turned off are turned back on and the wetting and drying conditions are adjusted to appropriate levels.

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

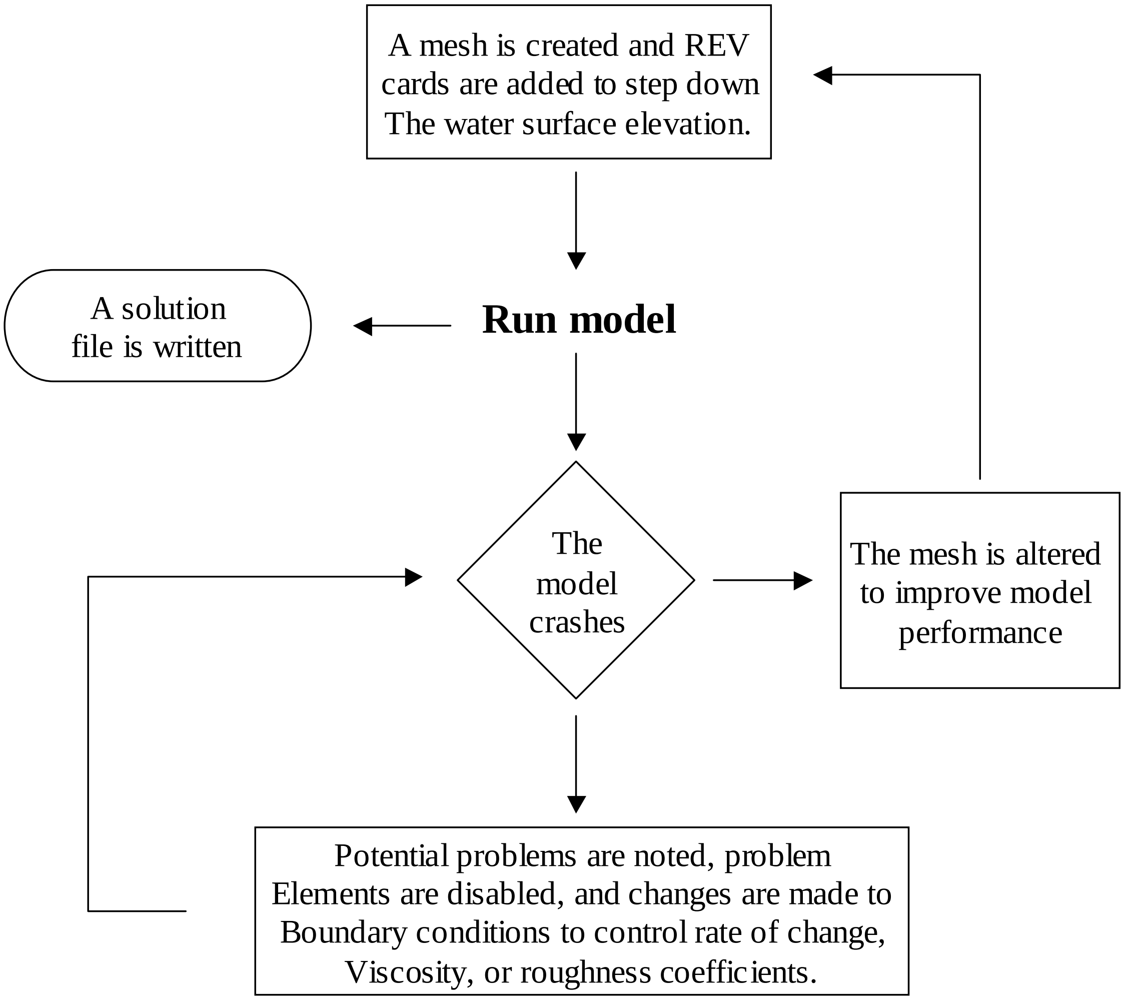


Figure 11: Decision support diagram for creating an RMA2 simulation

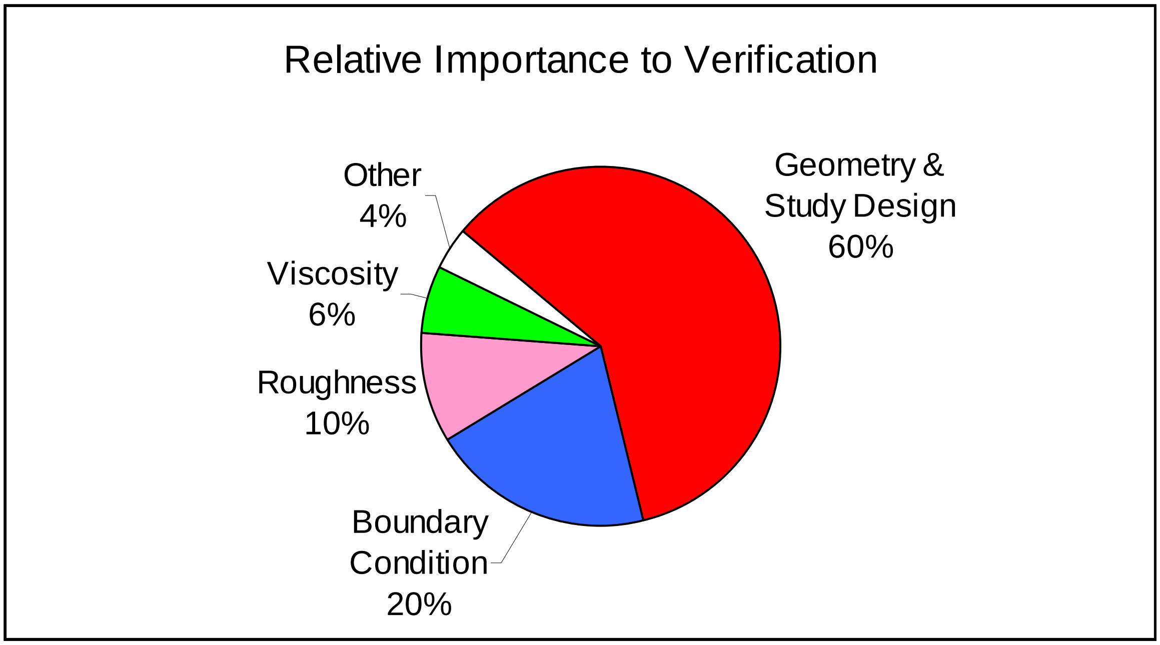


Figure 12: Relative importance of user defined variables to model calibration / verification. (From King 1997)

direction of flow. The data contained in the solution file can be further exported to a tab delimited file for use in other programs.

2.6.4 Model Calibration

Model calibration is a very important step in the model creation process. Although it might seem reasonable to assume that RMA2 would produce solutions that approximate real world conditions, changes in model geometry, boundary conditions, roughness and eddy viscosity can have a significant effect on the model results. It is possible to make educated guesses as to how these variables should be set, but a better approach is to adjust these variables such that the model calibrates against known field conditions. The RMA2 Users Guide suggests that geometry and study design are the most important factors for the creation of a reasonable flow model and that roughness and eddy viscosity may only account for 16% of the variation in the results (Figure12). Because these are the only variables the user can change midstream in the modeling process, they become the variables that are manipulated during the calibration process. Problems with study design and mesh geometry should be addressed as early in the modeling process as possible.

SMS allows the user to input files containing point measurements of depth, velocity, or water surface elevation for model calibration. These measurements can be compared to model estimates of observation parameters by interpolating calculated values from the nearest set of nodes. SMS can graphically display a chart of computed vs. observed values or can export these data to a comma delimited file. By making changes to model geometry and material parameters, the results can be adjusted to better match observed conditions. If observations are available at more than one flow, the model can be calibrated at one flow and then validated against another. If the validation can be achieved at the highest and lowest flows of interest, it is likely that the entire discharge domain will be reasonably represented.

The RMA2 Users manual warns the user against assuming that model calibration and validation is a two-step process. The arguments are sound and are presented as follows:

> 1. All field data are in error, and sometimes dramatically in error. Thus, they are not an absolute standard (a necessary characteristic of calibration), and may not be even a good approximate standard.
> 2. Field measurements include a variety of effects that may not be reproduced in the model (for example: groundwater flow into the model).
> 3. Conditions often change between field surveys, mandating that coefficients should also change (for example: differences in bed forms at different flows may dictate a change in bed roughness coefficients).
> 4. Most natural waterways cannot be adequately characterized by two field data sets. Five or ten may be needed, but available resources usually limit the field data to a non-ideal level.
> 5. If the model reproduces one field data set adequately, but not the second, you must decide whether to: a) Proceed with modeling, conceding an incomplete verification, b) Continue adjusting/revising to obtain a balanced quality of reproduction, c) Conduct a re-analysis/re-collection of field data.

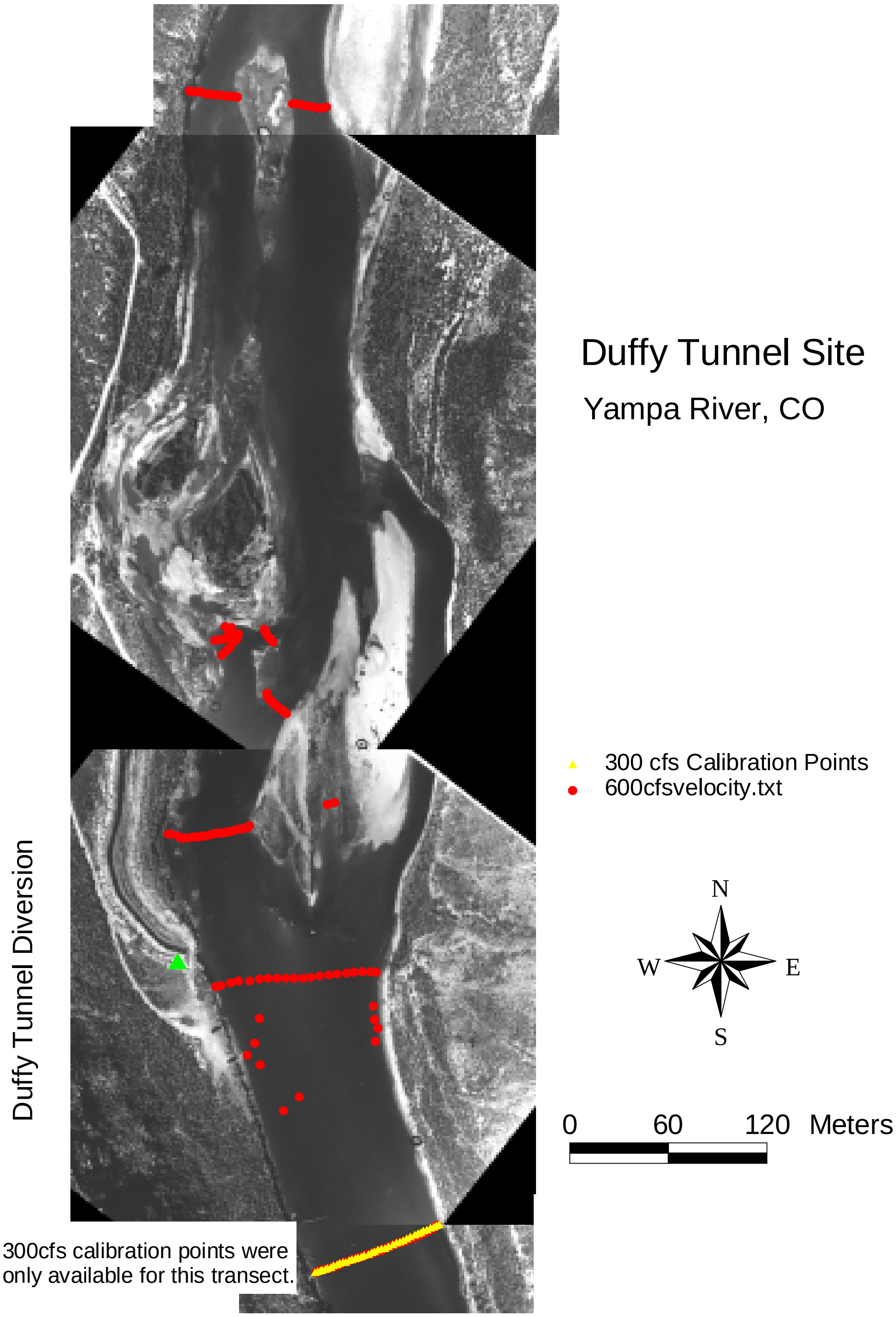


Figure 13: Distribution of calibration measurements for the Duffy Tunnel model.

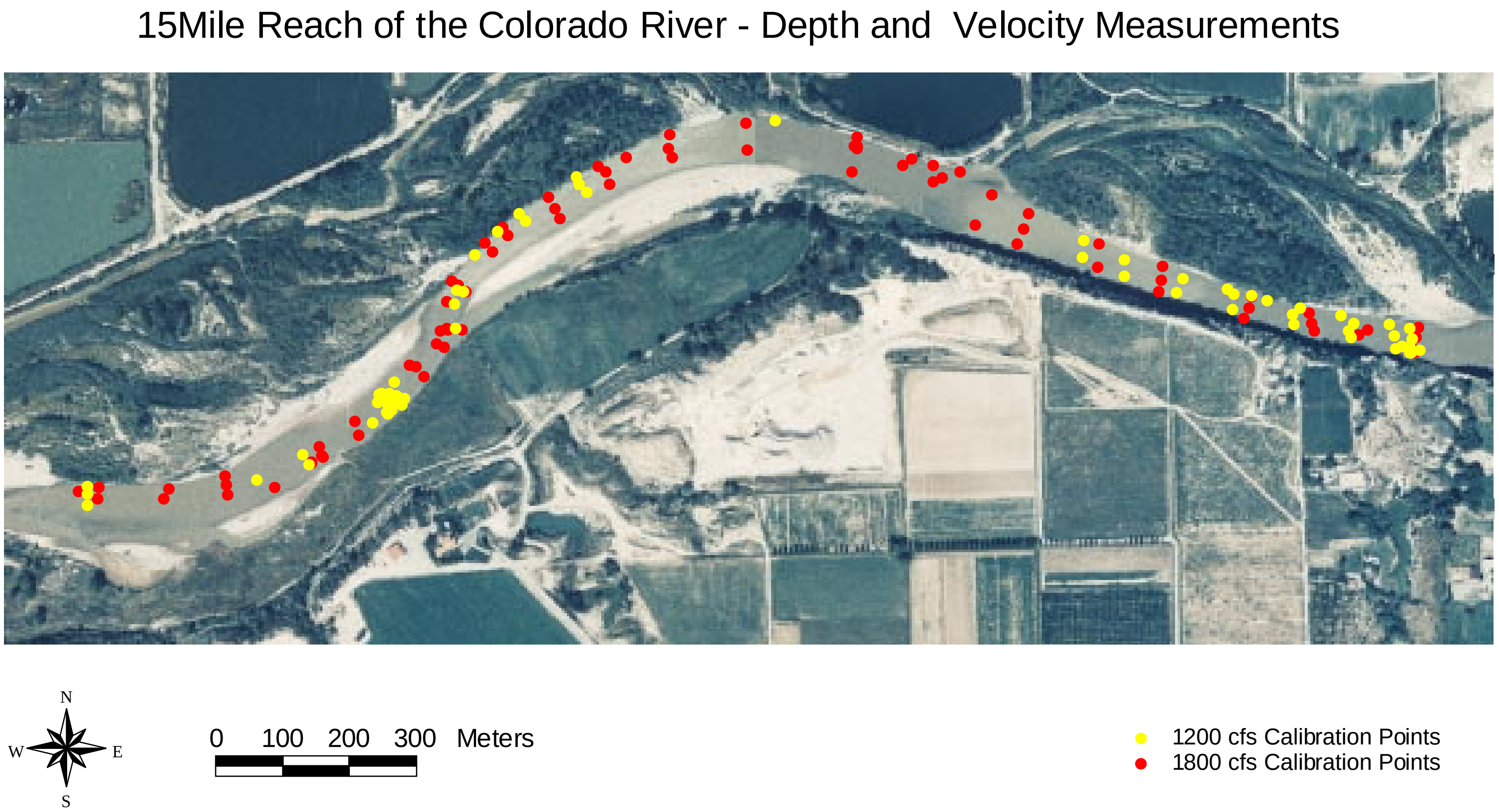


Figure 14: Distribution of calibration points for the 15 Mile Reach

During the 1999 Duffy Tunnel survey, almost no calibration data were collected, and those data that were available were of very poor quality. During the 1998 survey, however, several cross-sectional surveys were conducted to gather velocity information and to estimate discharge. Two sets of cross-sectional surveys were conducted in flows of interest, one at approximately 17 cms (600 cfs) and one at approximately 8.5 cms (300cfs) (Figure 13). Calibration data for the Colorado River were collected using the ADP and were not in cross-sectional form. The idea was to obtain calibration points over a wide spatial distribution and a large distribution of depth and velocity (Figure 14).

2.7 Analysis of Model Results

Once a two-dimensional model has been calibrated and, if possible validated, the modeling results must be analyzed in a manner that allows for an evaluation of the influence of river hydraulics on fish habitat. The Instream Flow Incremental Methodology (IFIM), of which PHABSIM is a part, defines microhabitat by the spatial attributes of a physical location. The spatial attributes of interest are depth, velocity, cover and substrate (Bovee et al., 1998). Although cover and substrate are mentioned as important components, they are rarely evaluated in anything more than a qualitative way. In general, fish habitat availability is determined by weighted usable area, a metric consisting of the percentage of suitable depths and velocities for a species of interest.

As stated in section 1.1, the ability of a 1-D model to adequately describe the availability of mico-habitat has been called into question, as have habitat suitability curves based on micro-habitat observations. In order to take advantage of the spatially explicit nature of two-dimensional modeling results, and to get away from micro-habitat availability, a decision was made to group areas of similar depth and velocity based on meso-habitat types including riffles, pools, and runs. There are at least two advantages to using this type of habitat grouping to evaluate habitat availability: 1) habitat groupings should be less sensitive to small errors in hydraulic modeling results, assuming that most of the habitat does not fall on classification boundaries and, 2) the use of a discrete number of meso-habitat units makes it easier to initially correlate habitat availability with fish abundance because small differences in habitat preference are minimized while larger scale trends in habitat utilization become more evident. As more information is gathered on habitat utilization by fish species, meso-habitat definitions can be refined to better represent how small variations in depth and velocity affect riverine species.

The smallest spatial scale to which an organism responds to patch structure is its “grain”, and the grain of a particular patch is dependent on the species and the temporal scale of interest (Kotliar and Weins, 1990). Through consultation with Rick Anderson of the Colorado Division of Wildlife, it was determined that adult fish (>15 cm) in the study reaches probably did not respond to habitat on a scale much smaller than 1 m^2 at any time-scale. With this consideration, it was decided that a 1 m^2 grid would be the smallest appropriate grain size to use in determining habitat from depth and velocity calculations.

Meso-habitat units were calculated by exporting depth and velocity information for each node in the mesh from SMS into a text file. This text file was used to create TINs of depth and velocity in ArcInfo. A 1m^2 lattice was then interpolated from each of the TINs in ArcInfo to create grids for depth and velocity. Conditional statements then evaluated each cell in the two grids and assigned habitat types based on a combination of depth and velocity as provided by the CDOW (Table 1).

Table 1: Depth and velocity categories for assignment of meso-habitat types

Habitat Types	Depth (m)	Velocity (m/s)
Wetted Sand	0.01 - 0.2	< 0.15
Shoal	0.2 - 0.5	< 0.15
Shallow pool	0.5 - 1.0	< 0.15
Medi -pool	1.0 - 2.0	< 0.15
Deep pool	> 2.0	< 0.15
Wetted area	.01 - 0.2	0.15 - 0.6
Shoal-run	0.2 - 0.5	0.15 - 0.6
Shallow run	0.5 to 1.0	0.15 - 0.6
Medi-run	1.0 to 2.0	0.15 - 0.6
Deep run	> 2.0	0.15 - 0.6
Shallow riffle	< 0.2	0.6 - 1.5
Riffle	0.2 to 0.5	0.6 - 1.5
Deep riffle	0.5 to 1.0	0.6 - 1.5
Very deep riffle	> 1.0	0.6 - 1.5
Shallow rapid	< 0.5	> 1.5
Deep rapid	> 0.5	> 1.5

The meso-habitat types provided by the CDOW fall into four basic categories based on estimated velocity distributions for each type. Pools are defined in this study as those areas having small velocities (<0.15 m/s), while runs have higher velocities (0.15-0.6 m/s) and riffles and rapids have even greater velocities (0.6-1.5 m/s and >1.5 m/s respectively). Habitat groupings based on velocity are further broken down into meso-habitat types based on depth and velocity by separating shallow areas from those that are relatively deep.

2.7.1 Fragstats

Fragstats is a spatial pattern analysis program for quantifying landscape structure and pattern developed by Kevin McGarigal and Barbara Marks at Oregon State University (http://www.fsl.orst.edu/lter/data/software/fragstat.htm). It can be downloaded at no cost, is totally automated, and can be used to evaluate vector or raster images on DOS or Unix platforms. The program computes a number of metrics including a variety of area metrics, patch density, size and variability metrics, edge metrics, shape metrics, core area metrics, diversity metrics, and contagion and interspersion metrics (McGarigal and Marks, 1995).

Fragstats was used to analyze the structure of meso-habitat taken from 1 m^2 habitat grids. Although Fragstats calculates a large number of spatial metrics, only a few of those metrics were considered to be of much use in evaluating the effect of declining flows on fish habitat. With this in mind, each metric that Fragstats calculated was considered with regard to its biological significance for instream flows. Of the metrics provided by Fragstats, the two that seemed to be most applicable were the Shannon Diversity Index and the Modified Simpsons Diversity Index.

A number of studies have shown that habitat diversity is positively correlated with species diversity in aquatic environments (Schlosser, 1982; Shields *et al.*, 1994; Eckmann, 1995; Katano *et al.*, 1998). The idea is that in a landscape with a large diversity of habitats, there is more opportunity for individual species to find habitat patches that they can exploit (Connell, 1980). In communities with significant predator/prey interactions, the diversity of habitats may provide the opportunity for prey species to avoid predation by seeking habitats that predators are either unwilling or unable to utilize (Power, 1992).

Diversity indices, however, have received much criticism from ecologists because they convey no information on the actual composition of a community, but are really just measures of richness and evenness (McGarigal and Marks, 1995). These critisisms are valid, especially in cases where some habitat types are considered more valuable than others, as is often the case when looking at single species or lifestages. For this study, however, it was determined that because the fish community was largely composed of a large number of species, including introduced species, the goal of providing diversity composed of richness and evenness was appropriate and would provide an excellent metric for comparisons against the wetted perimeter method.

A few other metrics were used to evaluate the heterogeneity of fish habitat. Mean Nearest Neighbor Distance is the distance from the edge of one habitat type to the nearest patch of the same habitat type. A fish must move further to find similar habitat as the nearest neighbor distance increases. At some point, fish may find themselves unable or unwilling to escape competition or predation because the distance to needed or preferred habitat is too great. The Interspersion and Juxtaposition index may be another important index of heterogeneity. The Interspersion and Juxtaposition index describes adjacencies between different patch types and represents the degree to which habitat types are interspersed. Interspersion and juxtaposition approaches 100 when all patch types are equally adjacent to all other patch types (McGarigal and Marks, 1995). Some species require multiple habitat types to meet their needs. Species may spend time in one habitat type when feeding and another habitat type when resting. When habitat types are well interspersed, the distance a fish must travel to meet all its habitat needs is generally minimized.

Chapter III – RESULTS

The finite element mesh used in two-dimensional modeling is a creation of art as much as science yet can have a significant impact on the hydraulic simulation. Although changes to the mesh are generally handled at the beginning of the modeling process, the process of mesh generation is ongoing and the final mesh can truly be considered a result of the modeling process. During this study both the Duffy Tunnel and 15-Mile reach mesh geometries were modified many times. In general, the time required to create the final mesh exceeded a month for each of the study sites. The final mesh for the Duffy Tunnel site included 9,655 elements and 28,323 nodes with an average elemental area of 20.50 ± 0.32 m^2 (95%CI). Nodal spacing was approximately 2 meters laterally by 3 meters in the streamwise direction. The final mesh for the 15-Mile reach consisted of 22,319 elements and 62,697 nodes with an average elemental area of 12.50 ± 0.15 m^2 (95%CI). Nodal spacing was approximately 1.5 meters laterally by 2.5 meters in the streamwise direction.

RMA2 makes a large number of options available to the user. During this study, many different options were evaluated, some in greater detail than others and the choice of which options to use was the result of the modeling process. Both the Duffy Tunnel and 15-Mile Reach models used the automatic dynamic assignment of turbulent exchange coefficients by Peclet number option. The Peclet option (PE card) assigns eddy viscosity based on the unique size and calculated velocity within each element. The Peclet number (P) defines the relationship between the velocity, elemental length, fluid density, and E using the function:

$$E = \frac{\rho u dx}{P} \quad \text{……………………………………..} \ (3.1)$$

where ρ = 1g/m^3

u = average elemental velocity (m/s)

dx = length of element streamwise direction (m)

E = Eddy viscosity (Pascal-sec)

This method was chosen over the assignment of a single eddy viscosity measurement because initial observations suggested that the model was most likely to crash in areas of high velocity. After assignment using the Peclet number option, much of the bias against high velocities was removed because those areas were assigned higher eddy viscosities. In fact, with the Peclet option chosen, most of the problems ended up being in areas of flow separation in eddy pools where velocities were small.

Roughness can be assigned by either Manning n or Chezy C and can be assigned as a static value or by using the automatic roughness coefficient assignment by depth option. Roughness is highly variable and can be very hard to define in large rivers. For this reason, a decision was made not to over-delineate roughness in this study. On the Duffy Tunnel reach, five different material types were used, though two basic material types describe the roughness for almost the entire study reach. Material types are mesh areas that use a single set of coefficients to assign bottom roughness. On the 15-Mile reach, three basic material types were used with one material type accounting for most of the mesh and the other two roughness types used exclusively in riffle areas. The automatic roughness coefficient assignment by depth option was used on both sites. With this option, roughness is assigned using the following formula:

$$n = \frac{RDRO}{AveDep^{RDCOEF}} + RDRM * e^{\frac{AveDep}{RDDO}} \quad \text{..............................(3.2)}$$

where AveDep = Average depth of the element

RDRO = Base Manning's n-value

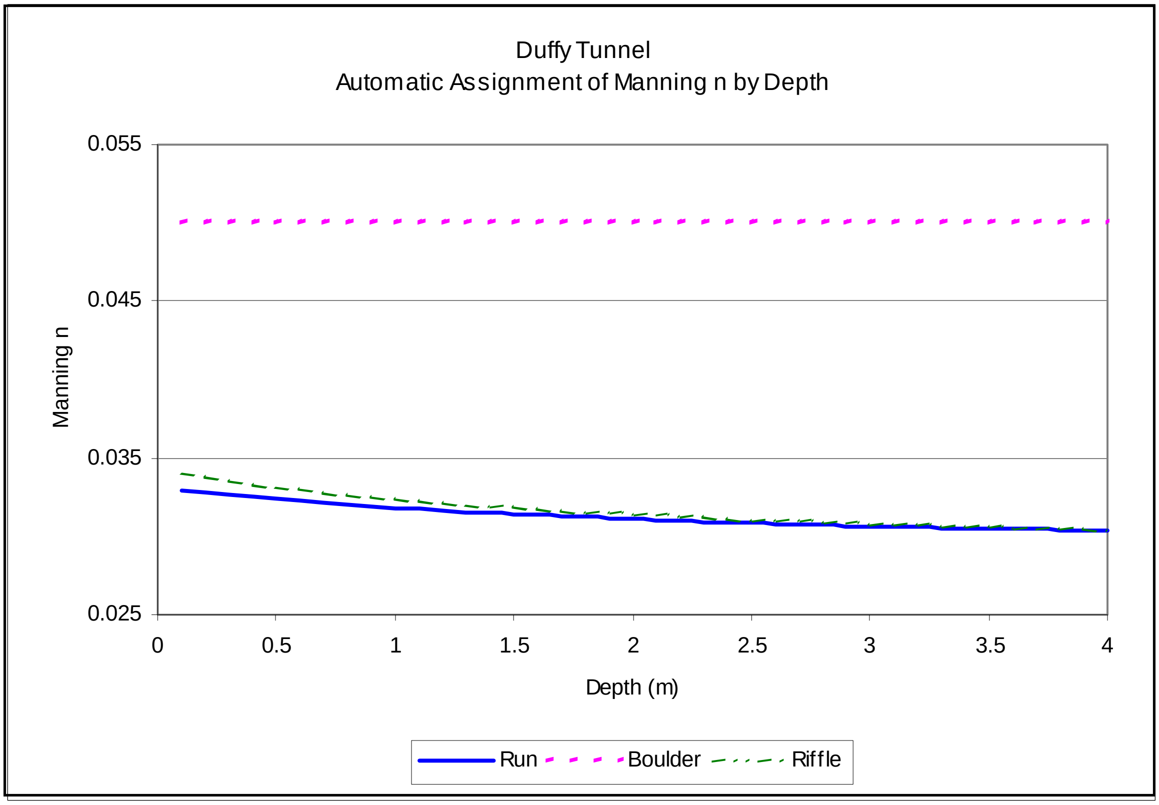
RDCOEF = Roughness by depth coefficient
RDRM = Manning’s n-value for vegetated water
RDDO = Depth at which vegetation affects roughness

Roughness assignment curves created using this function are shown in Figure 15 for the material types used at each study site.

The process of wetting and drying is of concern to anyone interested in modeling over a wide range of discharges. SMS provides two different methods for dealing with wetting and drying of the finite element mesh; elemental elimination and marsh porosity. Elemental elimination is the original wetting and drying method for RMA2. This method dries an entire element if any one node on that element has a computed depth less than a specified value. The element is re-wet when all nodes have a computed depth greater than another specified value. The other method available is marsh porosity. Marsh porosity allows an element to convey water through a proportion of the element until all nodes in the element are considered dry thereby allowing elements to transition gradually between wet and dry conditions. Marsh porosity and elemental elimination can be used in conjunction. Although the use of marsh porosity can result in a more realistic representation of the wetting and drying process, it comes at additional computational cost. All efforts to include marsh porosity in this modeling process ended in failure. As such, models were run using only the elemental elimination method with a nodal dry depth of 0.001 meters and a nodal wet depth of 0.01 meters as specified in the DE card. In the 15 Mile reach model, it was sometimes necessary to have a small number of elements turned off in order to obtain a stable solution.

3.1 Model Calibration

As stated in section 2.4.4, model calibration is an important part of the modeling process because reasonable values for many of the input parameters cannot be evaluated



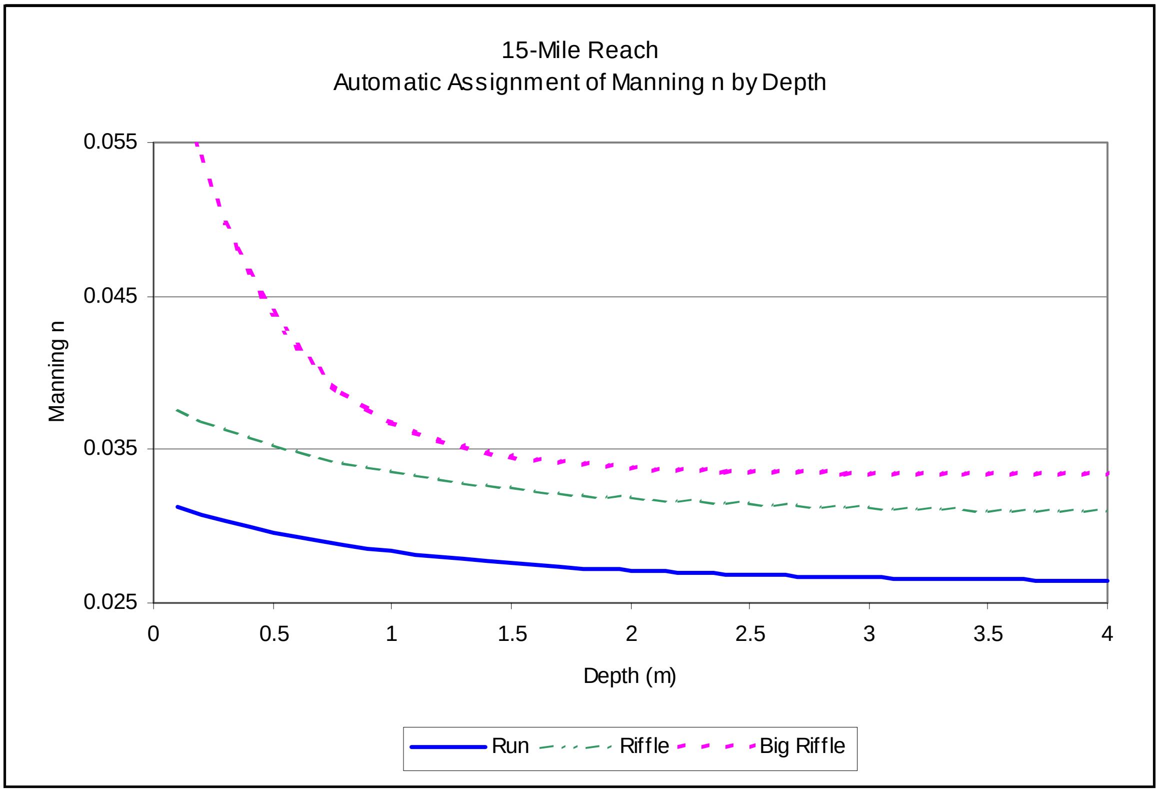


Figure 15: Chart showing final functions used automatic assignment of Manning n by depth option in SMS

objectively. The goal of calibration is to modify input parameters until the computed results match to real world observations of depth and velocity.

There are several ways in which goodness of fit between computed and observed values can be evaluated. In this study, the general goal of the calibration was to satisfy two conditions: 1) the slope of the regression between computed and observed should approximate slope of the 1:1 line, and 2) mean square error of the residual (observed minus computed) should be minimized. These conditions were evaluated simultaneously for depth and velocity, but where the trends diverged, preference was given to calibrating velocity measurements and having a regression line with a slope of 1.0. Velocities were given preference over depths, as they were more likely to be influenced by changes in roughness or eddy viscosity. Changes in Manning n tended to produce changes in the slope of the regression line whereas changes in eddy viscosity did not. Eddy viscosity did, however, influence the mean square errors.

One hundred and sixty observations of depth and velocity were available for initial calibration of the Duffy Tunnel model and sixteen different simulations were run on the model to determine the most appropriate boundary conditions. A discharge of 16.99 cms (600cfs) was used for model calibration and the two factors that were changed were the coefficients for assignment of roughness by depth using Manning's n and coefficients for assignment of turbulent exchange using the Peclet number.

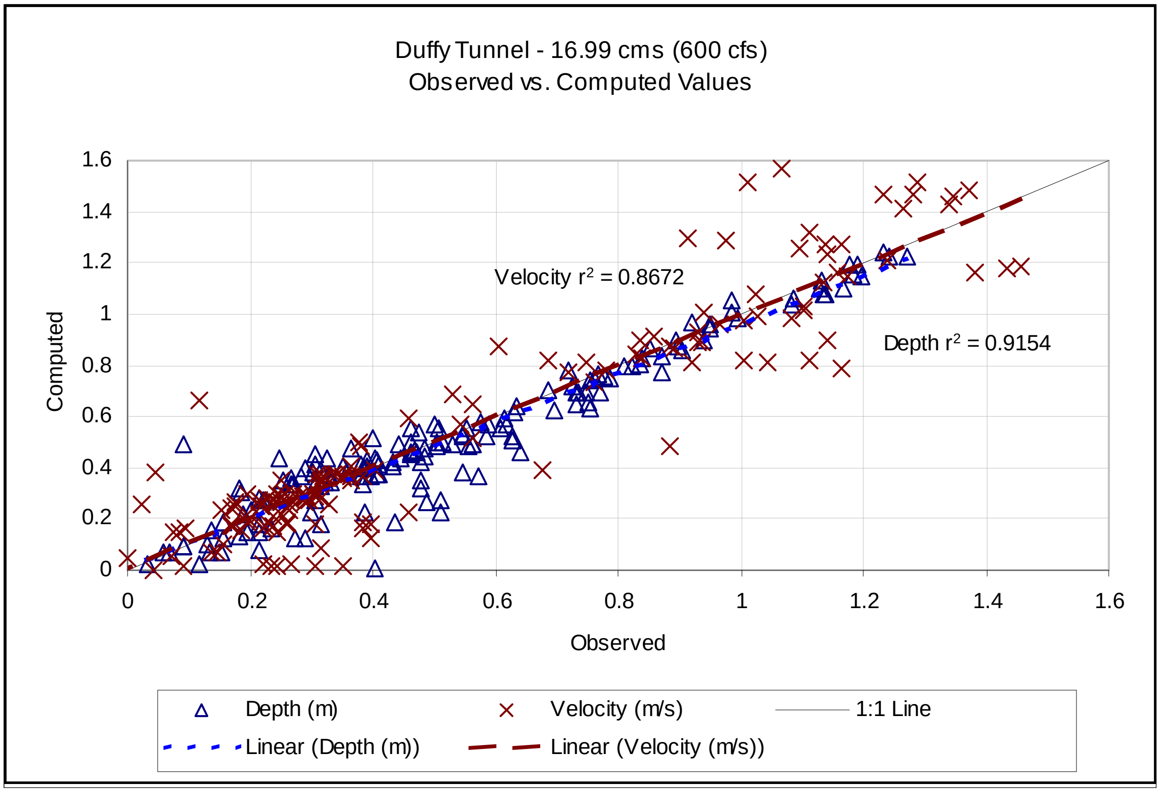
Calibration model DCal6 had the residuals with the lowest sum of squared errors, but the slope was much smaller than 1.0 (Table 2). Boundary conditions used in DcalD16 were chosen because it combined a low average error and moderate sum of squared error with a regression line that had a slope very close to 1.0. All subsequent Duffy Tunnel models used a Peclet value of 40 with a minimum velocity of 2.0 m/s and a scaling factor of 0.8. The scaling coefficient was used to reduce the absolute difference between the largest and smallest values of eddy viscosity. Final Manning n values for each material type are shown in Figure 15 and final calibration results are shown in Figure 16. As Figure 16 shows, there is much greater variability in velocity than there is in depth.

In this study it was possible to attempt to validate the model because calibration data were available at more than one discharge. Figure 17 represents the goodness of fit between calculated and observed values for 40 points, in a single cross-section, at a discharge of 8.50 cms (300 cfs). As shown by the residuals, the model appears to under-predict depth and demonstrates a strong trend towards over-predicting velocity at very low velocities and under-predicting relatively higher velocities at a cross-section.

A total of 80 observations were available at a discharge of 50.97 cms (1800 cfs) for calibration of the 15 Mile reach model and eighteen different simulations were run on the 15 Mile reach during the calibration phase (Table 3). No 15 Mile reach simulation resulted in a 1:1 regression line but model 15Cal17 resulted in the lowest sum of squared error and

Table 2: Duffy Tunnel model calibration. Average error and sum of square errors (SSE) are based on the residual (observed - computed). The correlation coefficient and slope are based on observed vs. computed.

	Velocity				Depth			
	Ave. Error	SSE	r^2	slope	Ave. Error	SSE	r^2	slope
DCal1	0.026	3.30	0.872	0.864	-0.003	1.28	0.912	0.939
DCal2	0.026	3.29	0.873	0.865	-0.003	1.28	0.912	0.939
DCal3	0.026	3.56	0.862	0.859	-0.002	1.30	0.911	0.940
DCal4	0.025	3.46	0.866	0.858	-0.002	1.28	0.912	0.938
DCal5	0.031	4.22	0.874	0.854	-0.007	1.30	0.911	0.939
DCal6	0.026	3.28	0.873	0.866	-0.003	1.28	0.912	0.938
DCal7	0.015	3.61	0.862	0.929	0.005	1.27	0.913	0.943
DCal8	-0.003	3.89	0.864	0.995	0.016	1.29	0.915	0.947
DCal9	-0.003	3.77	0.866	0.988	0.016	1.29	0.915	0.947
DCal10	-0.005	3.77	0.867	0.992	0.017	1.28	0.916	0.948
DCal11	-0.008	4.01	0.860	0.992	0.019	1.29	0.915	0.947
DCal12	0.022	3.80	0.855	0.911	-0.006	1.27	0.913	0.948
DCal13	0.020	3.94	0.849	0.906	-0.005	1.27	0.913	0.948
DCal14	0.007	3.78	0.860	0.956	0.008	1.26	0.914	0.946
DCal15	0.004	4.04	0.850	0.947	0.008	1.28	0.913	0.947
DCal16	-0.005	3.89	0.865	0.999	0.018	1.29	0.915	0.948



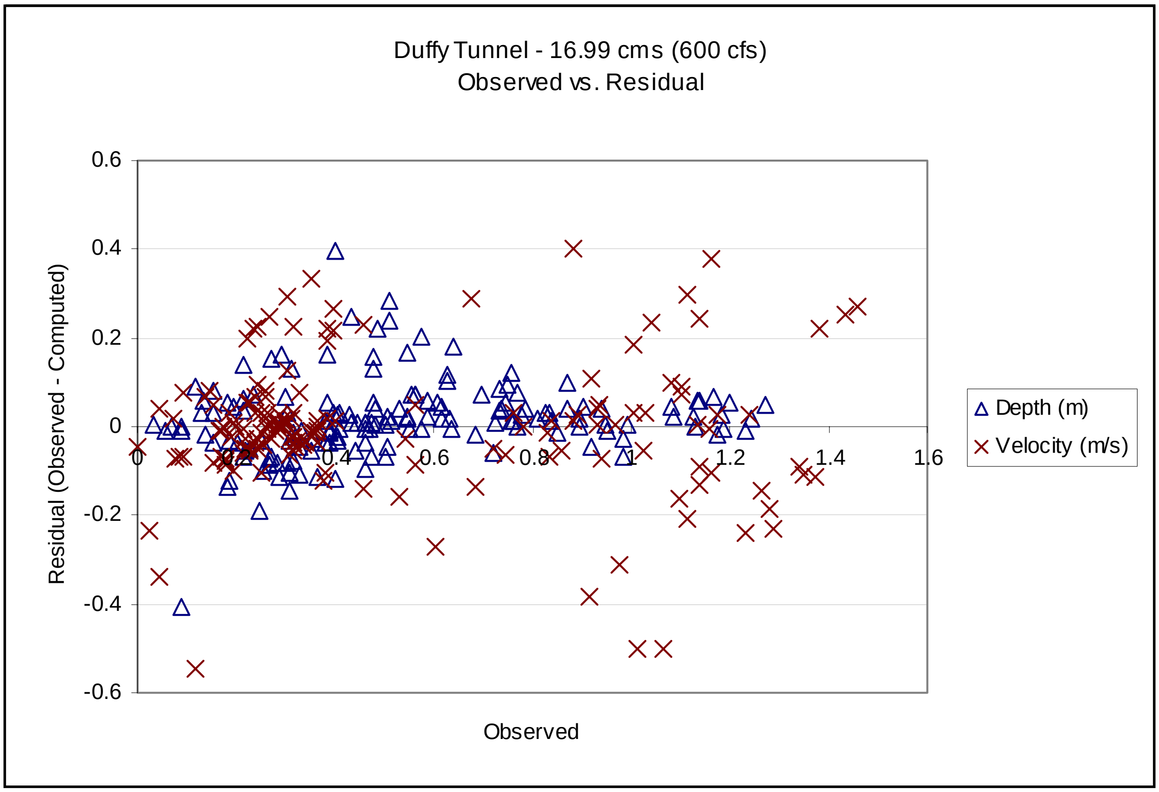
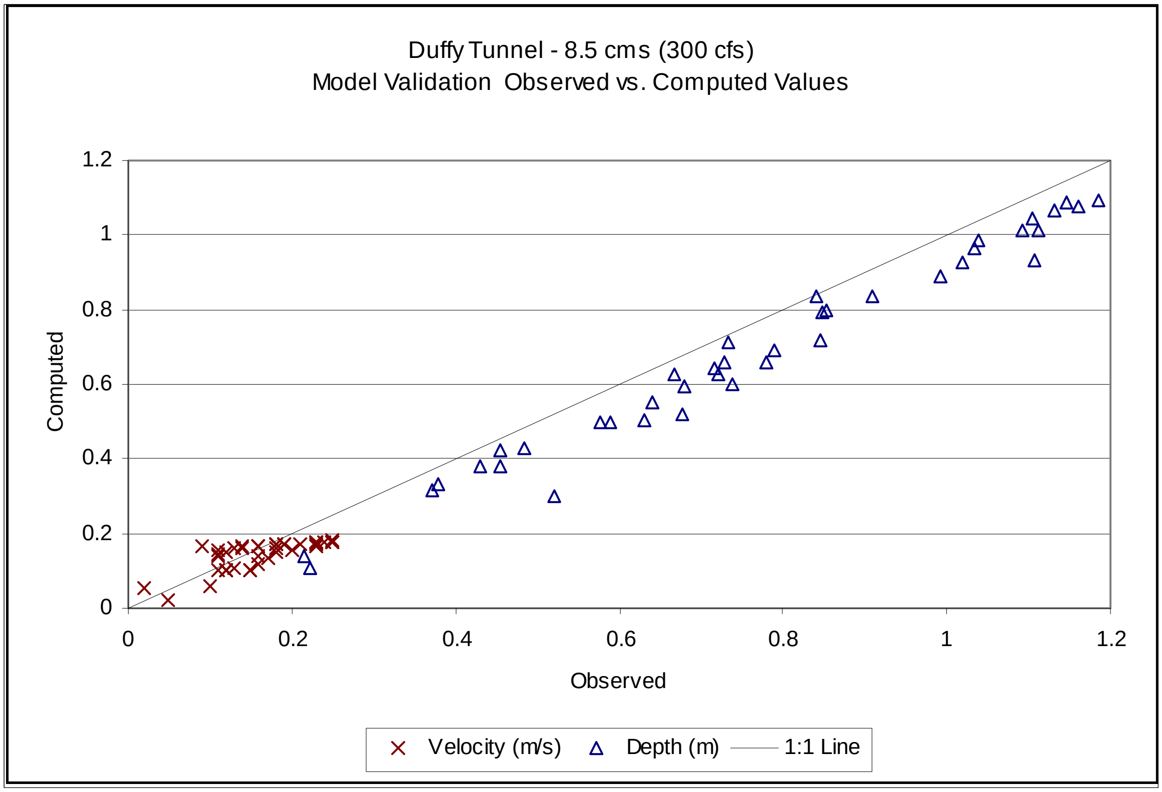


Figure 16: Duffy Tunnel Calibration - Observed vs. Calculated and Observed vs Residual



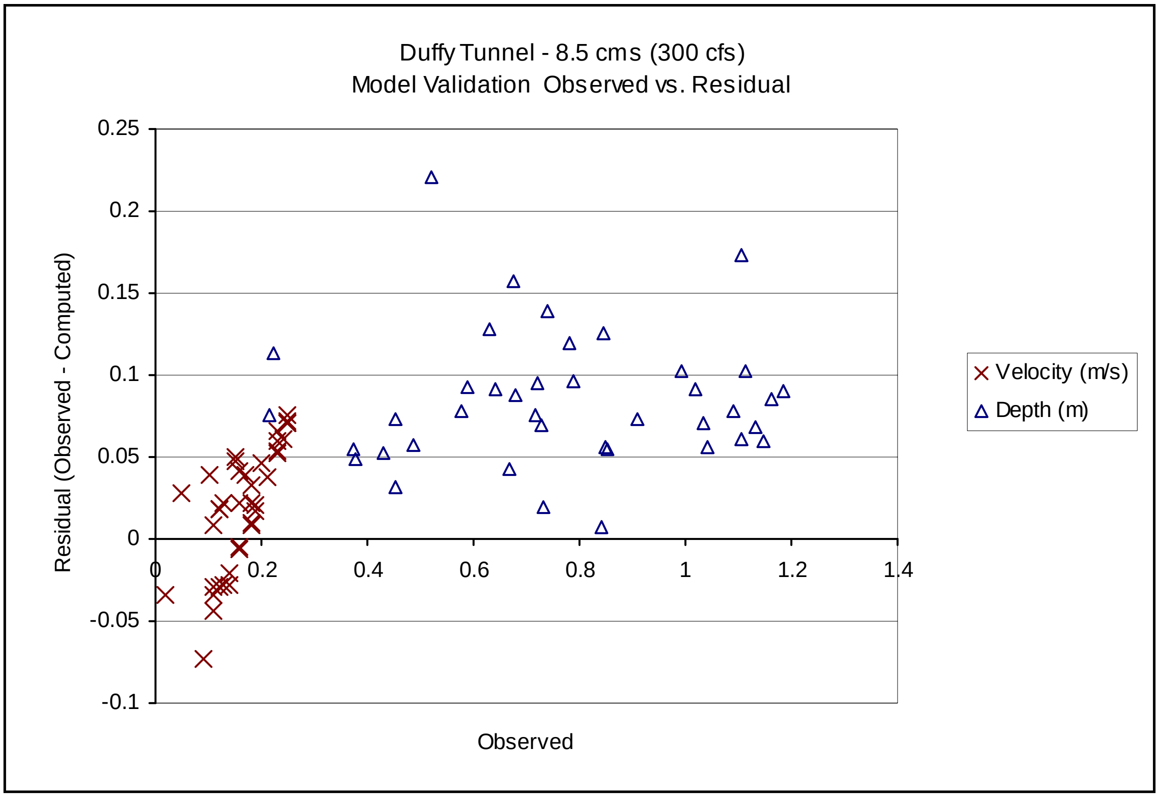


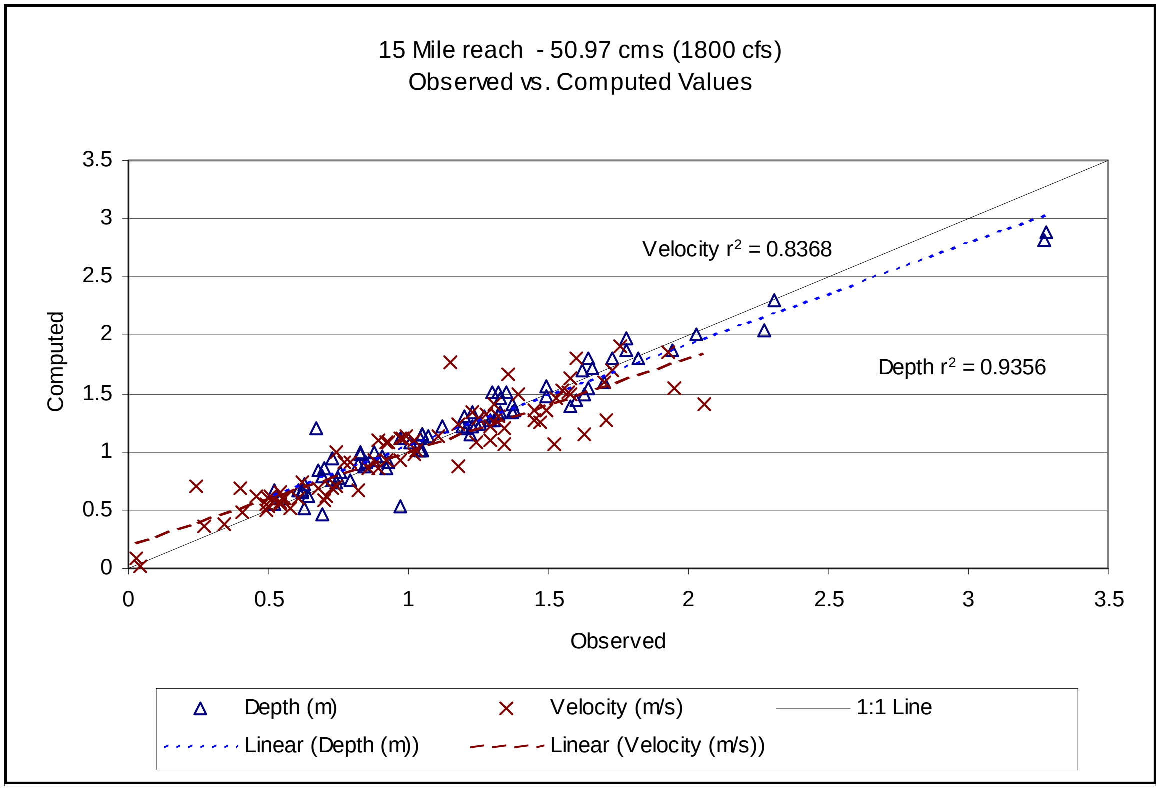
Figure 17: Duffy Tunnel Model Validation - Observed vs Calculated and Observed vs Residual

Table 3: Analysis of residuals for the 15 Mile reach model. Model names are shown in the left column and statistics related to the goodness of fit to field measurements are shown in the columns to the right.

Analysis of	Velocity				Depth			
Residuals	Mean	SumSq	r^2	Slope	Mean	SumSq	r^2	Slope
15Cal1	0.111	4.78	0.847	0.620	-0.146	3.22	0.942	0.855
15Cal2	0.080	3.92	0.852	0.659	-0.114	2.53	0.941	0.858
15Cal3	0.049	3.57	0.836	0.688	-0.082	2.03	0.941	0.862
15Cal4	0.040	3.33	0.843	0.703	-0.070	1.92	0.939	0.865
15Cal5	0.034	3.26	0.842	0.711	-0.065	1.86	0.939	0.866
15Cal6	0.032	3.24	0.841	0.716	-0.062	1.87	0.937	0.866
15Cal7	0.025	3.22	0.836	0.726	-0.057	1.83	0.936	0.867
15Cal8	0.016	3.11	0.835	0.745	-0.049	1.77	0.936	0.868
15Cal9	0.024	3.25	0.834	0.725	-0.056	1.81	0.937	0.867
15Cal10	0.018	3.12	0.835	0.747	-0.053	1.79	0.936	0.870
15Cal11	0.017	3.06	0.838	0.749	-0.051	1.77	0.936	0.869
15Cal12	0.014	3.03	0.839	0.755	-0.049	1.77	0.936	0.869
15Cal13	0.018	3.08	0.838	0.747	-0.051	1.78	0.936	0.869
15Cal14	0.014	3.03	0.839	0.754	-0.050	1.77	0.936	0.869
15Cal15	0.028	3.11	0.837	0.753	-0.038	1.69	0.936	0.869
15Cal16	0.015	2.99	0.837	0.775	-0.029	1.67	0.934	0.871
15Cal17	0.003	2.92	0.837	0.806	-0.021	1.60	0.936	0.873

average error. Based on the boundary conditions in 15Cal17, elements were assigned a Peclet value of 35, minimum velocity of 2.0 m/s, and scaling factor of 0.8. Final Manning n values for each material type, in this and all subsequent 15 Mile reach models, are shown in Figure 15. Figure 18 shows the relative goodness of fit for the calibrated 15 Mile reach model at a discharge of 50.97 cms (1800 cfs).

Again, data were available for model validation. Figure 19 shows the relative goodness of fit between 74 computed and observed values of depth and velocity on the 15 Mile reach at a discharge of 33.98 cms (1200 cfs). As shown by this figure, trends in the difference between the observed and computed are similar for velocity, but maybe a little larger than those found at a discharge of 50.97 cms (1800 cfs) for depth.



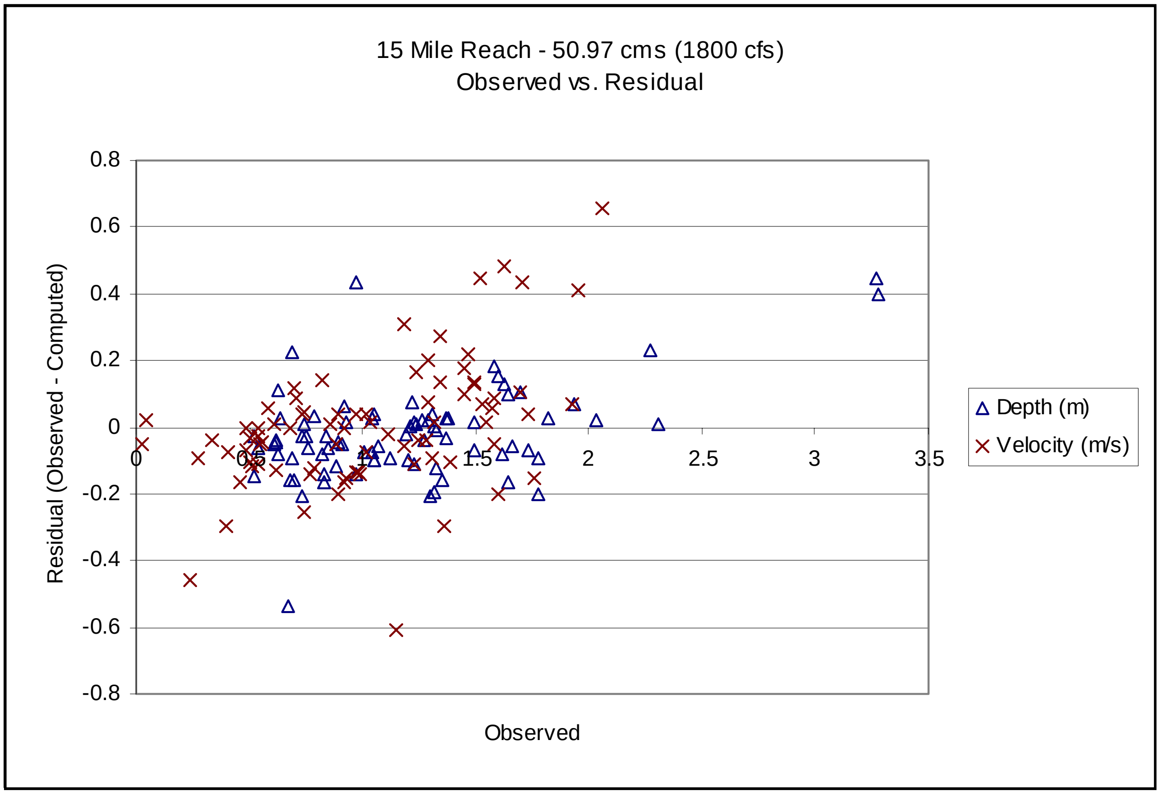
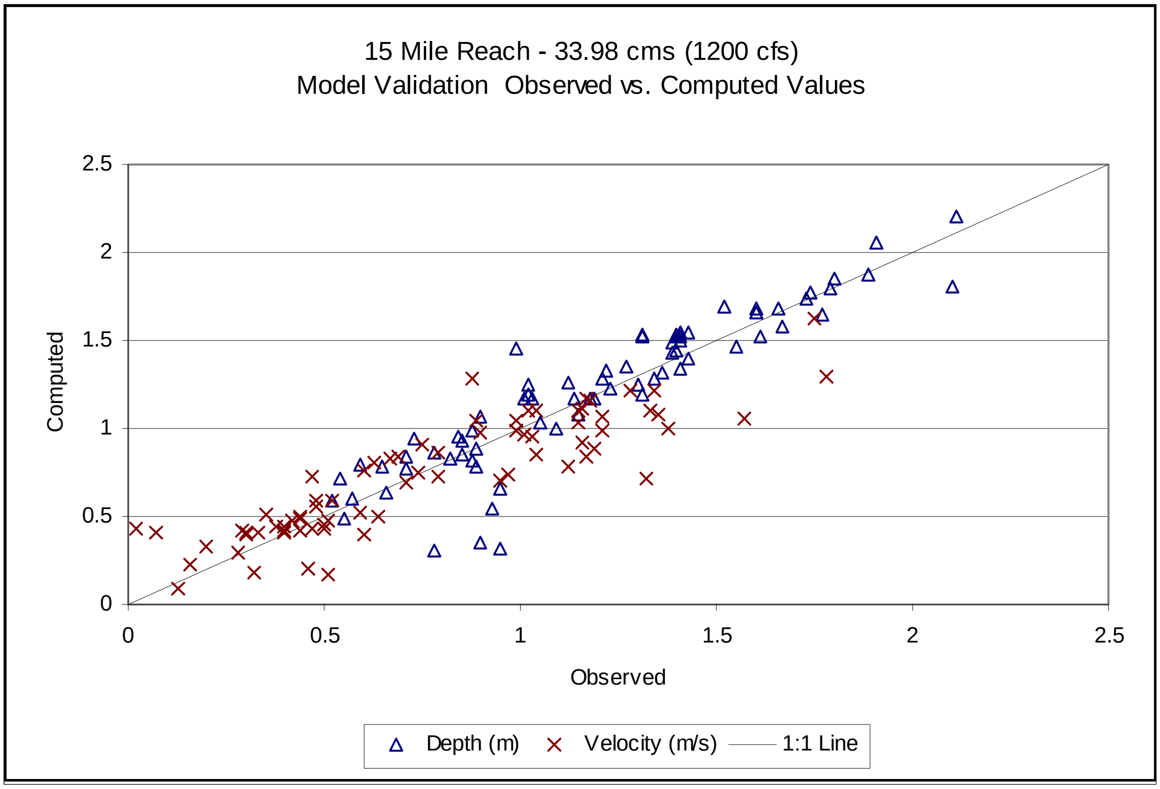


Figure 18: 15 Mile Reach Calibration - Observed vs Calculated and Observed vs Residual



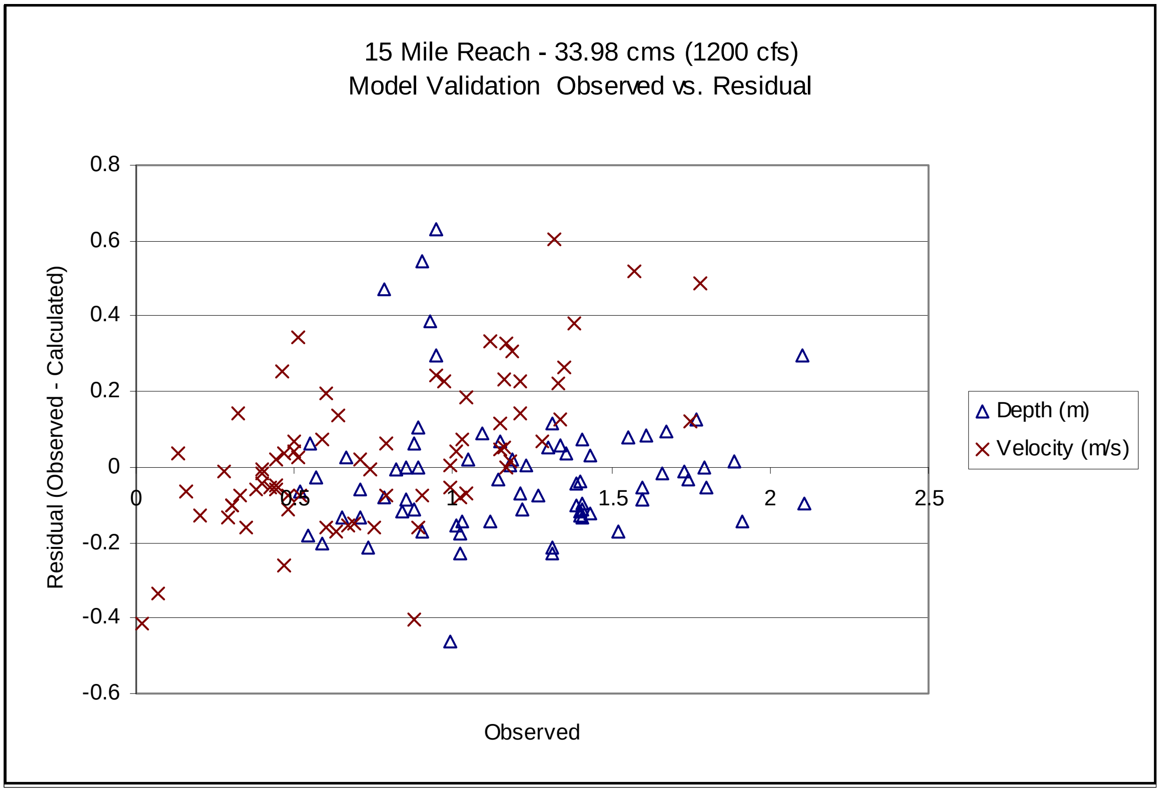


Figure 19: 15 Mile Reach Validation - Observed vs Calculated and Observed vs Residual

3.2 Meso-habitat availability, diversity, heterogeneity

The creation of maps showing meso-habitat availability over a range of flows was a primary goal of this study. After calibrating the RMA2 models, a number of flow simulations were run at each of the two sites. Figure 20 shows a typical RMA2 simulation as viewed in SMS. Velocity vectors are shown in black and represent magnitude and direction of flow. Depths and velocities calculated in RMA2 were exported to ArcInfo GIS and interpolated into a 1x1 meter grid where meso-habitat types were assigned using the meso-habitat criteria provided by the CDOW (Table 1, Figure 21). Grid coverages with meso-habitat type were created for each flow that was modeled. Figure 22 shows the total amount of meso-habitat available at each of the sites as a function of discharge.

As stated previously, an understanding of both the spatial distribution and temporal distribution of habitats is important to understand how changes in discharge are likely to affect fish communities. In theory, streams with high habitat diversity will support more diverse biological communities (Bovee, 1996b). Figures 23 and 24 show how indices of diversity, evenness, richness, mean nearest neighbor distance, contagion, and interspersion and juxtaposition change with discharge for the Duffy Tunnel and 15 Mile reaches, respectively. It is obvious from Figure 23 that diversity and interspersion are maximized at discharges close to 180 cfs, almost double the minimum discharge of 93 cfs recommended in the CDOW study of wetted perimeter. Trends in Figure 24 suggest that diversity and interspersion are maximized at discharges close to 1400 cfs on the 15 Mile reach.

3.3 Biological Validation

A major criticism of traditional instream flow methodologies has been that there have been very few studies that showed a biological response to modeled habitat availability though the response has generally been presumed. In this study, an attempt was made to

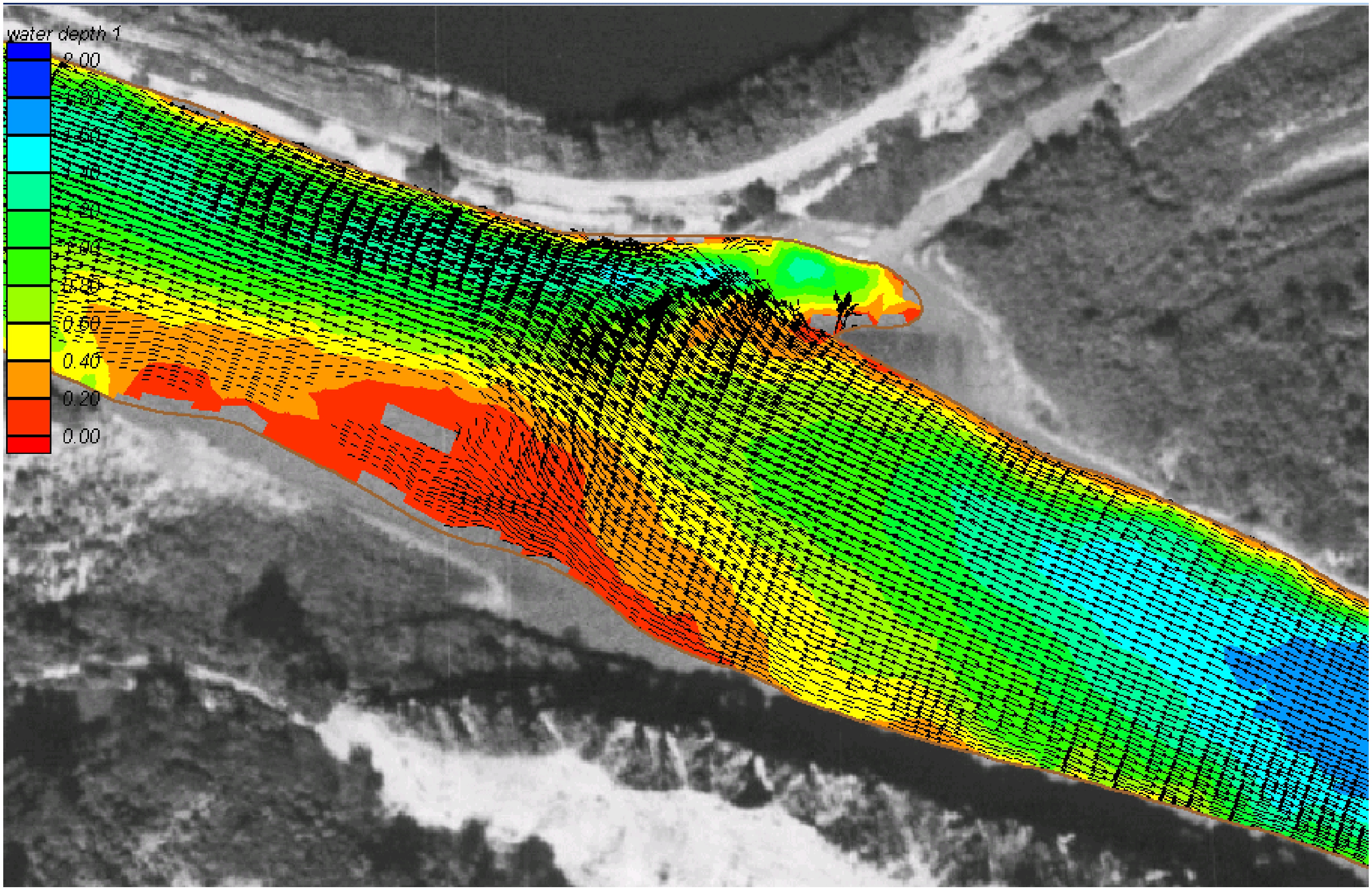


Figure 20: Depth and velocity in 2D SMS model. Magnitude of velocity is denoted by the size of the velocity vectors.

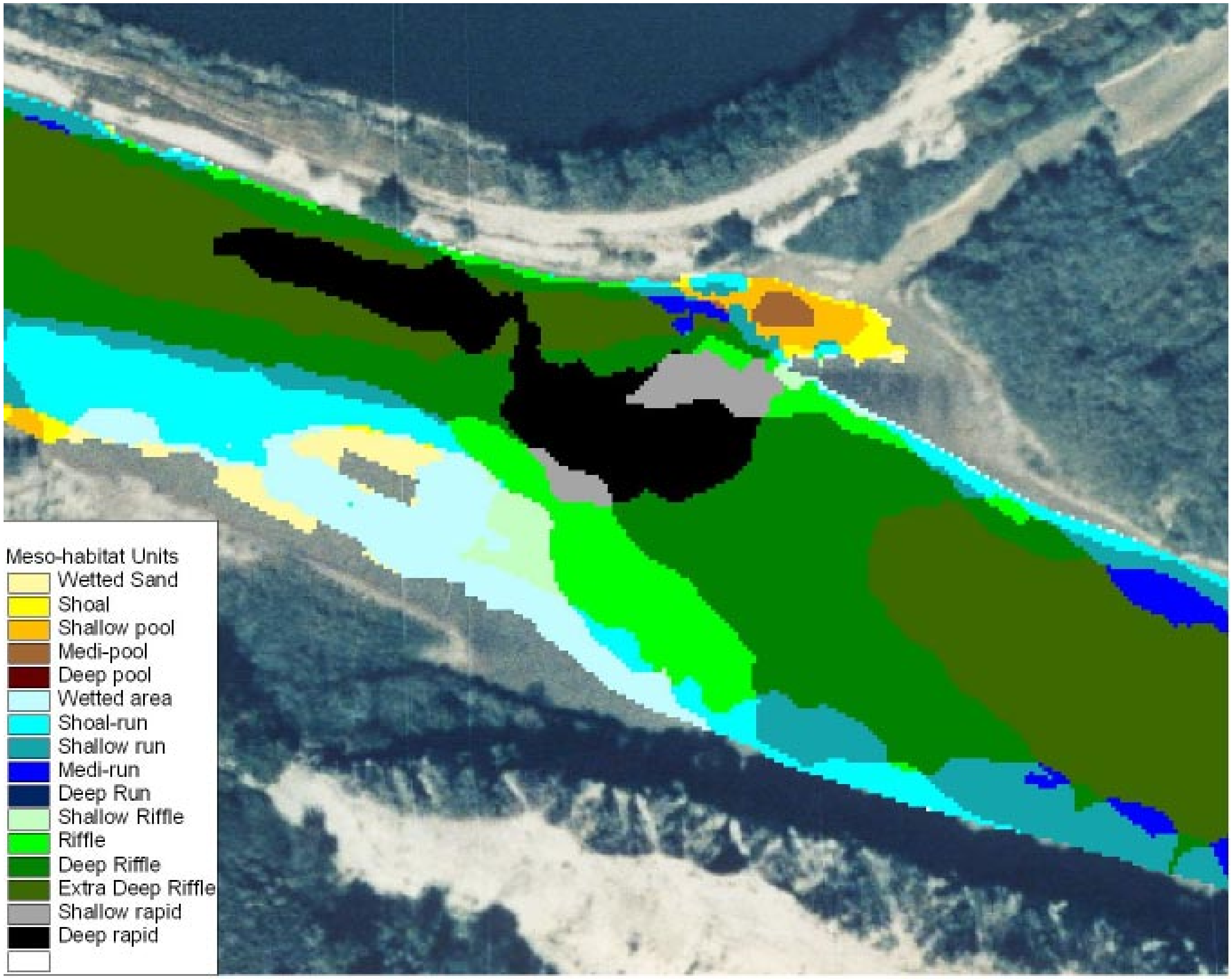
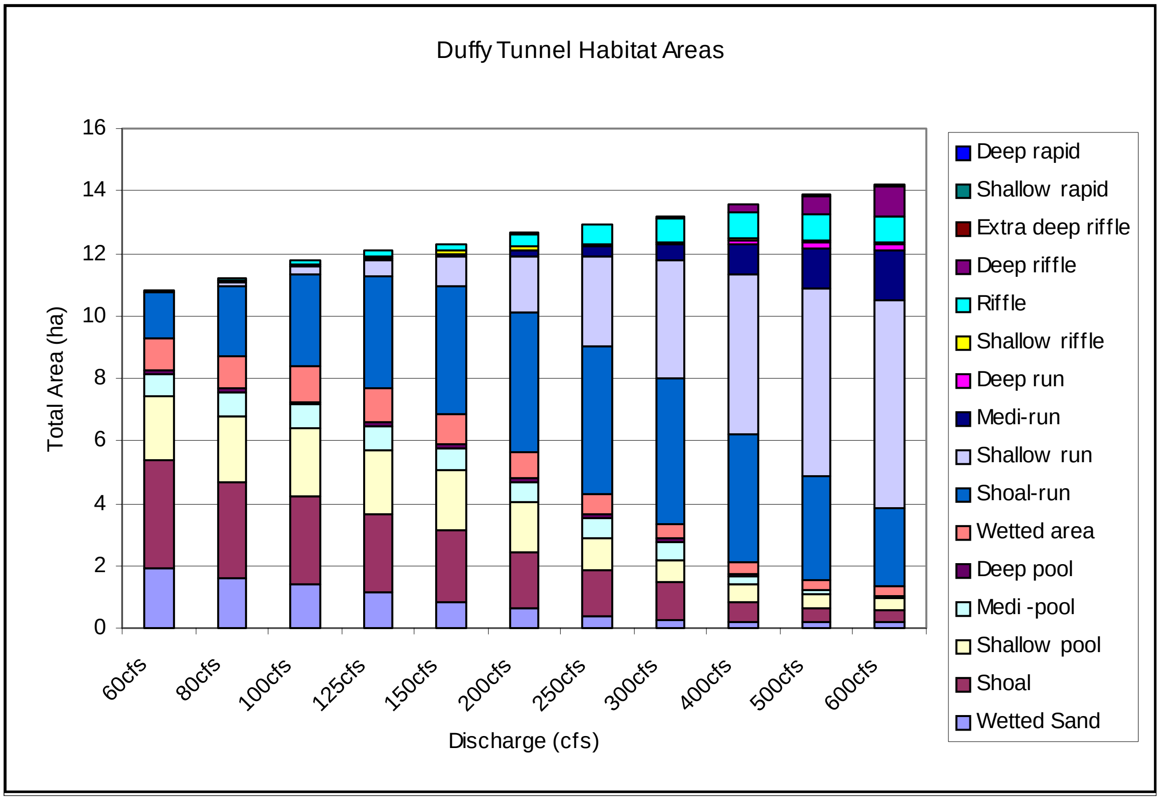


Figure 21: Meso-habitat types based on depth and velocity from the 2D model and DOW determined values for meso habitat types.



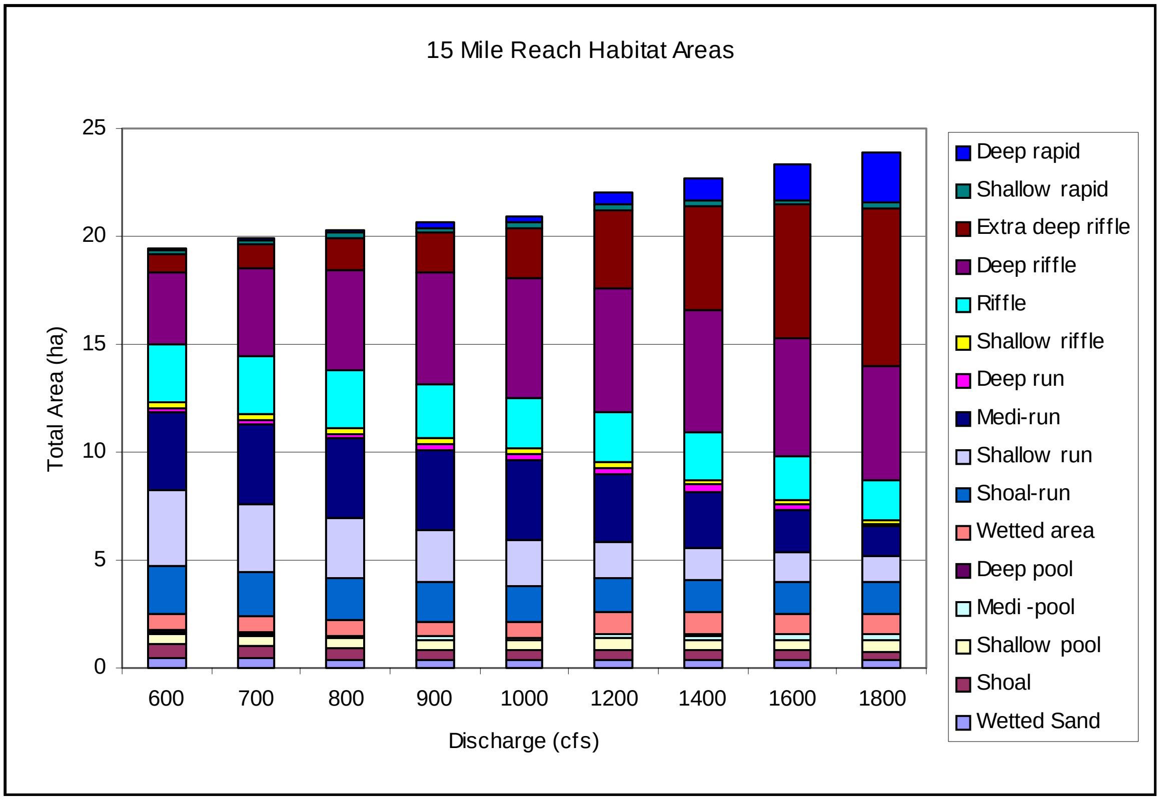


Figure 22: Meso-habitat availability as a function of discharge.

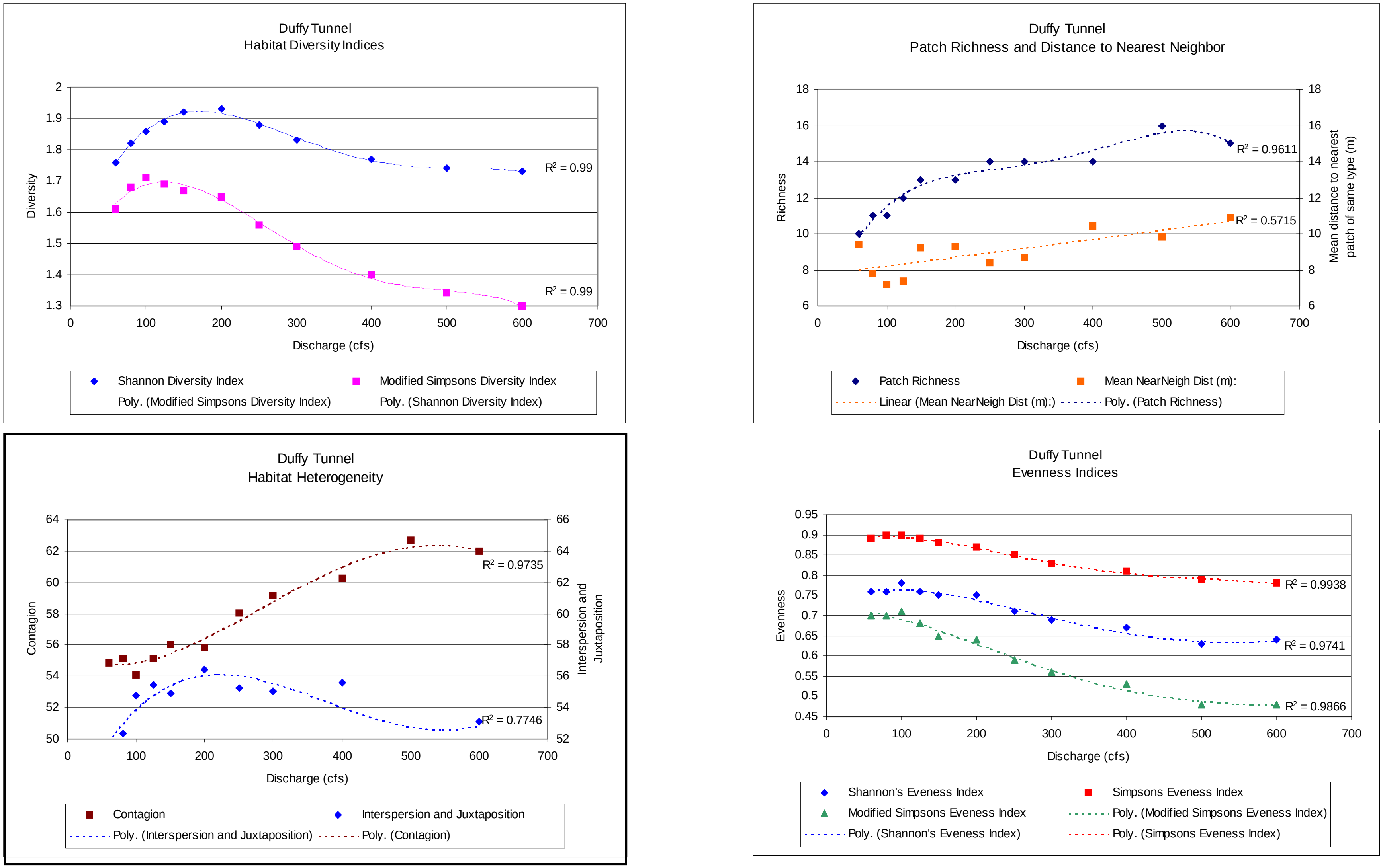


Figure 23: Indices of habitat heterogeneity for the Duffy Tunnel Reach

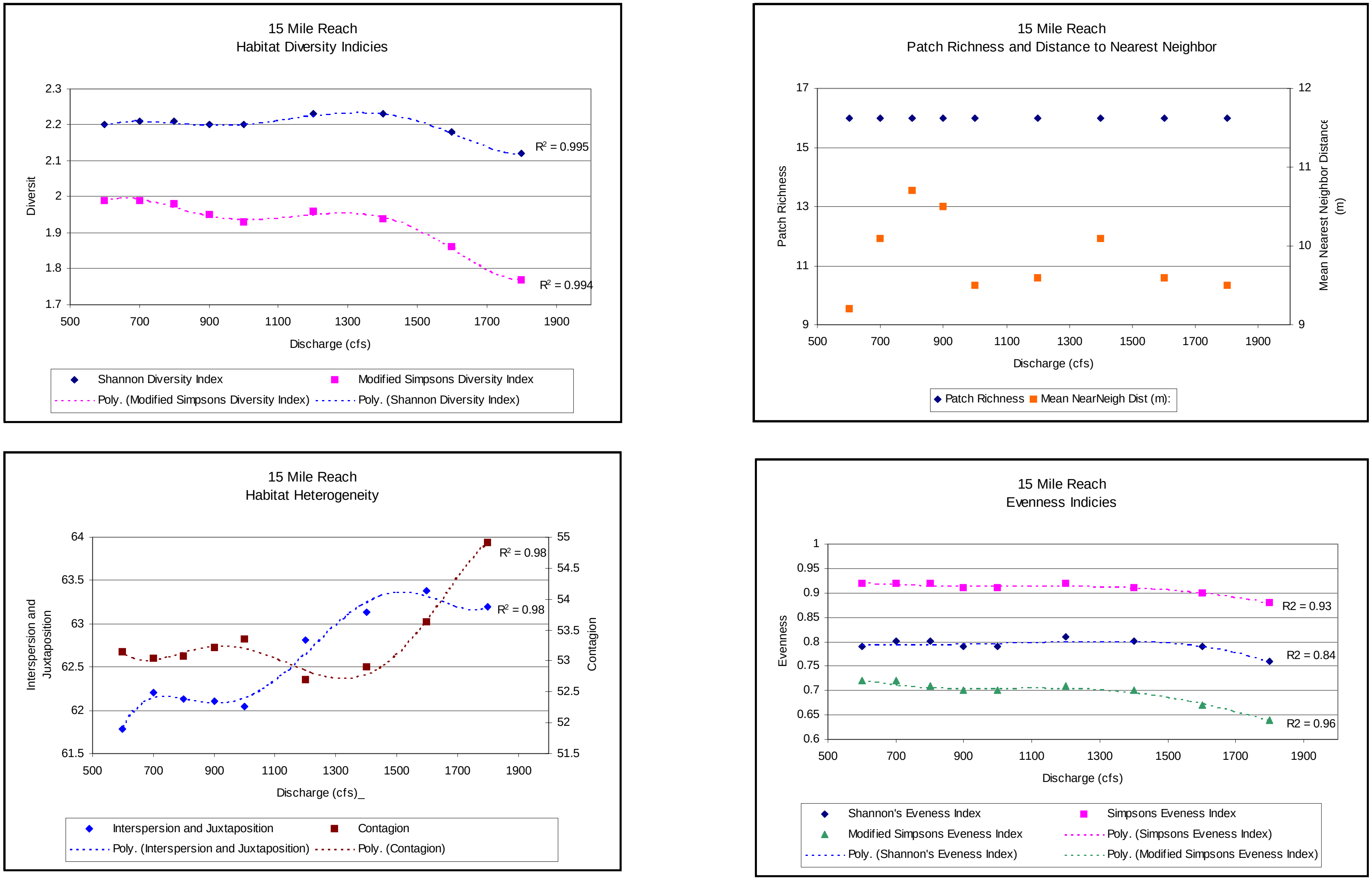


Figure 24: Indices of habitat heterogeneity for the 15 Mile Reach

determine whether preferences for habitat could be observed using results from electroshocking and 2-D meso-habitat.

For this study, fish were shocked in small reaches over a number of passes and the shocking reaches were mapped in the field (Table 3 & 4, Figure 25). The number of fish caught per pass was recorded and compared with the meso-habitat in that sub-reach. Meso-habitat area and number of fish were each normalized against sub-reach area and are presented as number of fish per pass per unit area vs. percent habitat type (Figures 26 – 28). In some cases, fish were correlated with more than one habitat type and habitat areas were combined. As such, the habitat conditions in terms of range of depth and velocity are defined on the x-axis of the graph. Positive correlations suggest a preference for sub-reaches with more of the defined habitat.

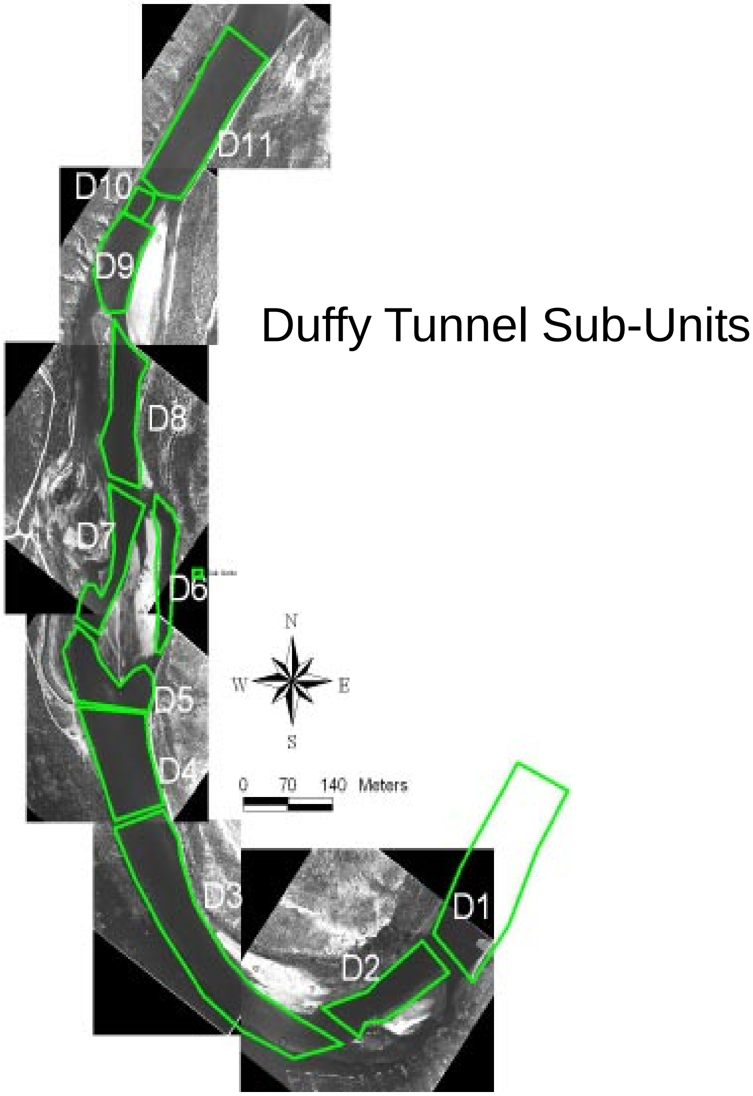
Two years of shocking data were available for the Duffy Tunnel site and both were used in the following analysis. Meso-habitat availability at 8.50 cms (300 cfs), the general discharge when most of the fish were collected, was calculated for each of the sub-reaches and compared against the number of fish captured in each sub-reach. Figure 26 shows two plots of habitat availability vs. species presence for two fish species at the Duffy Tunnel site. These plots are based on analysis using the meso-habitat definitions presented in Table 1 and show statistically significant trends for two species of interest. Although statistically significant, these relationships do not portray a large amount of information because so many of the subreaches had no Colorado pikeminnow (*Ptychocheilus lucius*) or smallmouth bass. In the Duffy Tunnel reach, only sub-habitat units three and eight had deep habitat and these were primarily where the Colorado pikeminnow and smallmouth bass were found. One advantage of using models is the ability to play “what if” scenarios. It was hypothesized that velocity might be much less important than depth at the Duffy Tunnel site and so a second set of meso-habitat criteria were developed based primarily on depth (Table 5).

Table 3: Electroshocking results for the Duffy Tunnel reach in 1998 and 1999 (Anderson R., Unpublished)

Year	1998						1999							
Sub-unit	D3	D4	D6	D7	D8	D11	D1	D2	D3	D6	D7	D8	D10	D11
Passes	5	4	2	2	4	3	3	3	6	2	3	4	3	4
Area (ha)	2.55	1.2	0.3	0.6	0.8	2	1.98	0.7	2.5	0.3	0.6	0.8	0.1	1.6
Recaptures	69	0	0	0	9	2	0	0	43	0	6	1	55	2
Bluehead	9	0	0	1	3	5	0	0	1	4	1	0	16	0
Flannelmouth	4	0	1	0	6	1	0	1	6	1	0	1	2	1
Roundtail chub	7	0	0	0	0	3	0	0	6	0	0	0	5	1
Colorado pikemin.	9	0	0	0	0	0	0	0	4	0	0	1	0	0
White sucker	143	4	5	22	23	16	0	1	70	6	24	13	68	26
White/Flannelm.	66	0	6	7	12	1	4	1	69	2	4	4	66	3
White/Bluehead	7	0	6	0	3	3	0	1	0	2	5	1	19	1
Carp	5	0	0	0	0	0	0	0	0	0	0	0	0	1
Channel catfish	4	0	0	0	0	1	0	0	18	0	0	2	1	0
Northern pike	14	3	0	0	2	0	0	0	6	2	0	4	2	0
Smallmouth bass	34	2	0	0	1	0	0	0	28	0	1	0	0	3

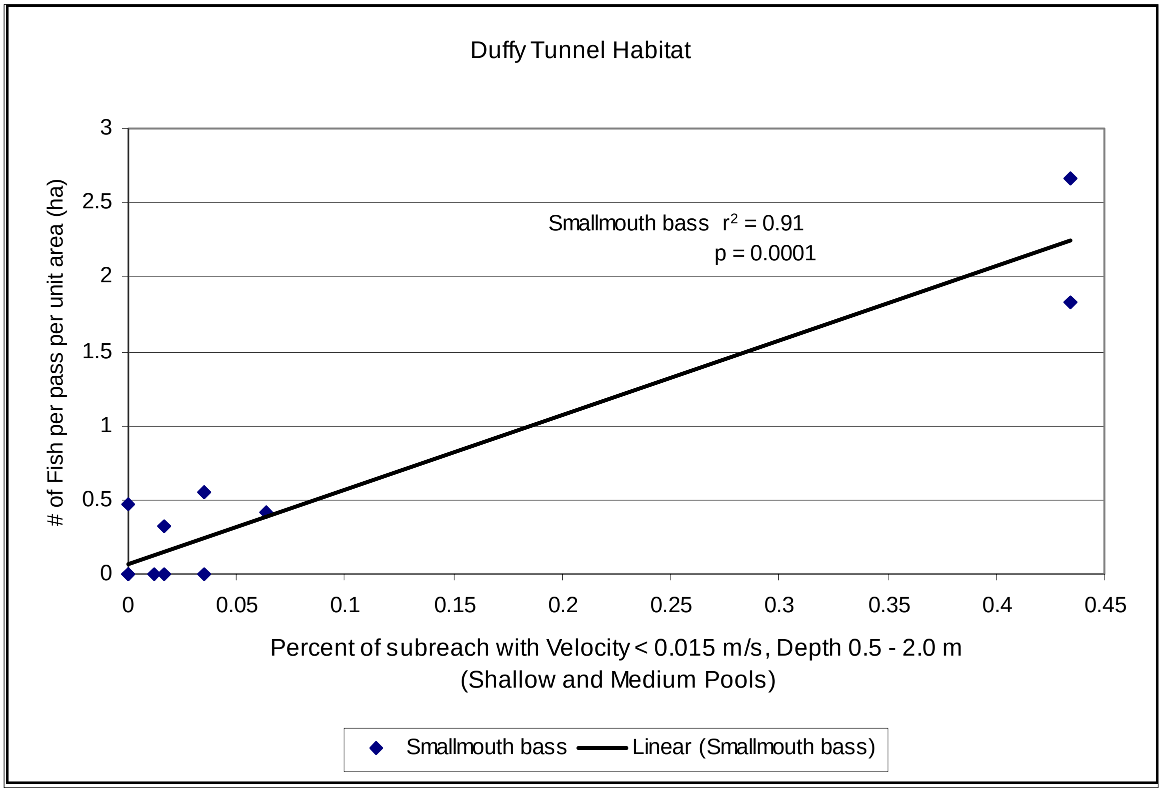
Table 4: Electroshocking results for the 15 Mile reach, summer 1999 (Anderson, R. Unpublished)

15 Mile Reach - 1999 Electroshocking Results					
SubUnit	Upper 1	Mid-up 2	Mid-mid 3	Mid-low 4	Lower 5
FISH (n)	804	812	308	688	640
Total Area (ha)	6.88	4.95	1.74	3.55	4.95
Bluehead	263	419	70	314	132
WhiteXbluehead	13	7	2	14	5
Flannelmouth	365	279	121	212	306
Whitexflannel	10	5	4	1	3
Channel catfish	33	26	11	46	28
Brown trout	3	5	0	5	1
Bluexflannel cross	2	0	1	2	0
Rainbow trout	1	0	0	0	0
Colorado pikeminnow	0	0	0	0	2
Roundtail chub	24	20	10	14	29
Carp	65	39	48	65	102
White sucker	23	12	26	13	21
Largemouth bass	1	0	4	0	3
Blackbull head	1	0	11	0	8
Green sunfish	0	0	0	2	0



15 Mile Reach Sub-Units

Figure 25: Sub-habitat units for Duffy Tunnel and 15 Mile Reach



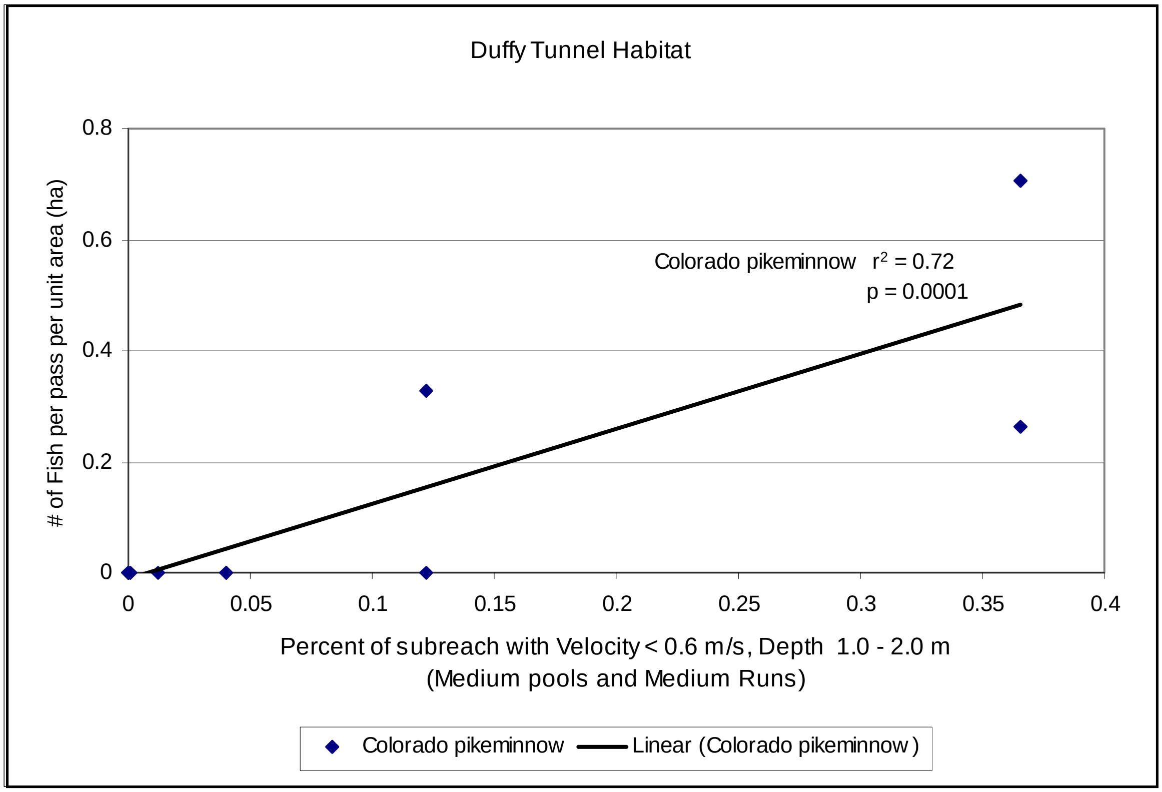
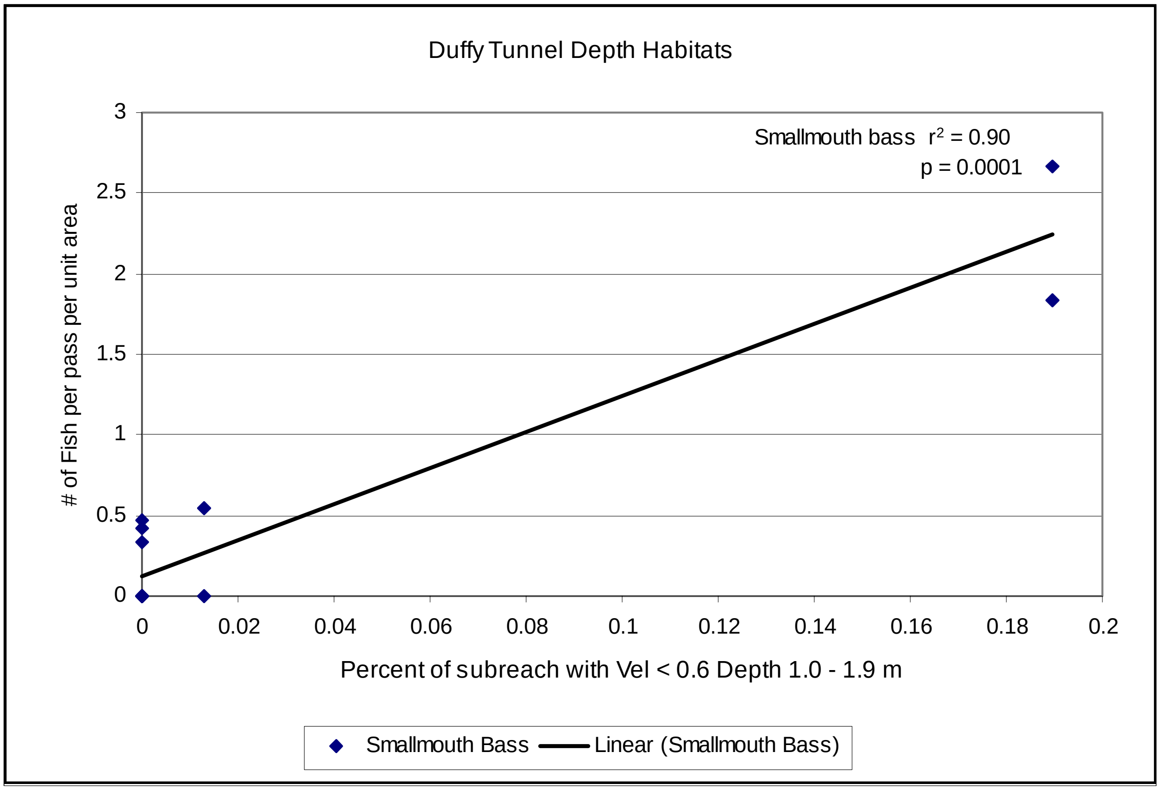


Figure 26: Correlations between meso-habitat availability and number of fish per unit area.



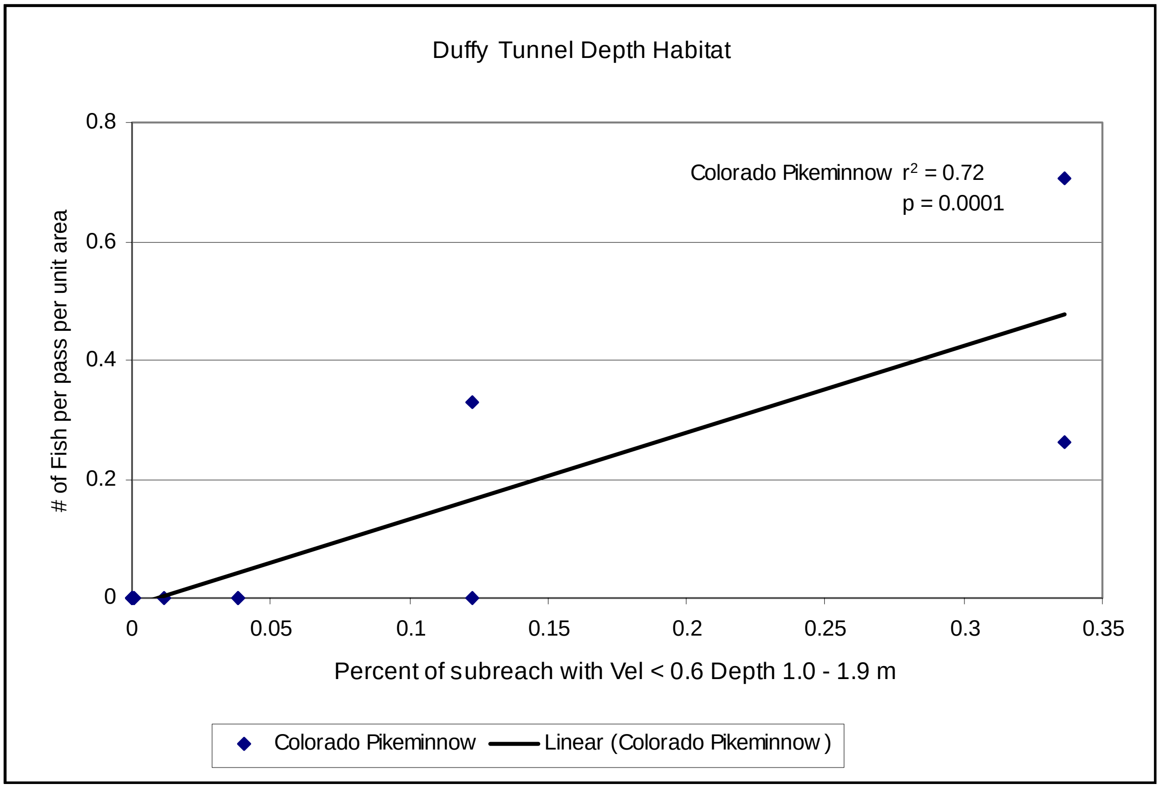


Figure 27: Correlations between meso-habitat availability and number of fish per unit area using depth based habitat criteria. The results area very similar to those in Figure 25, suggesting that changes in habitat definition did not improve the analysis of habitat utilization.

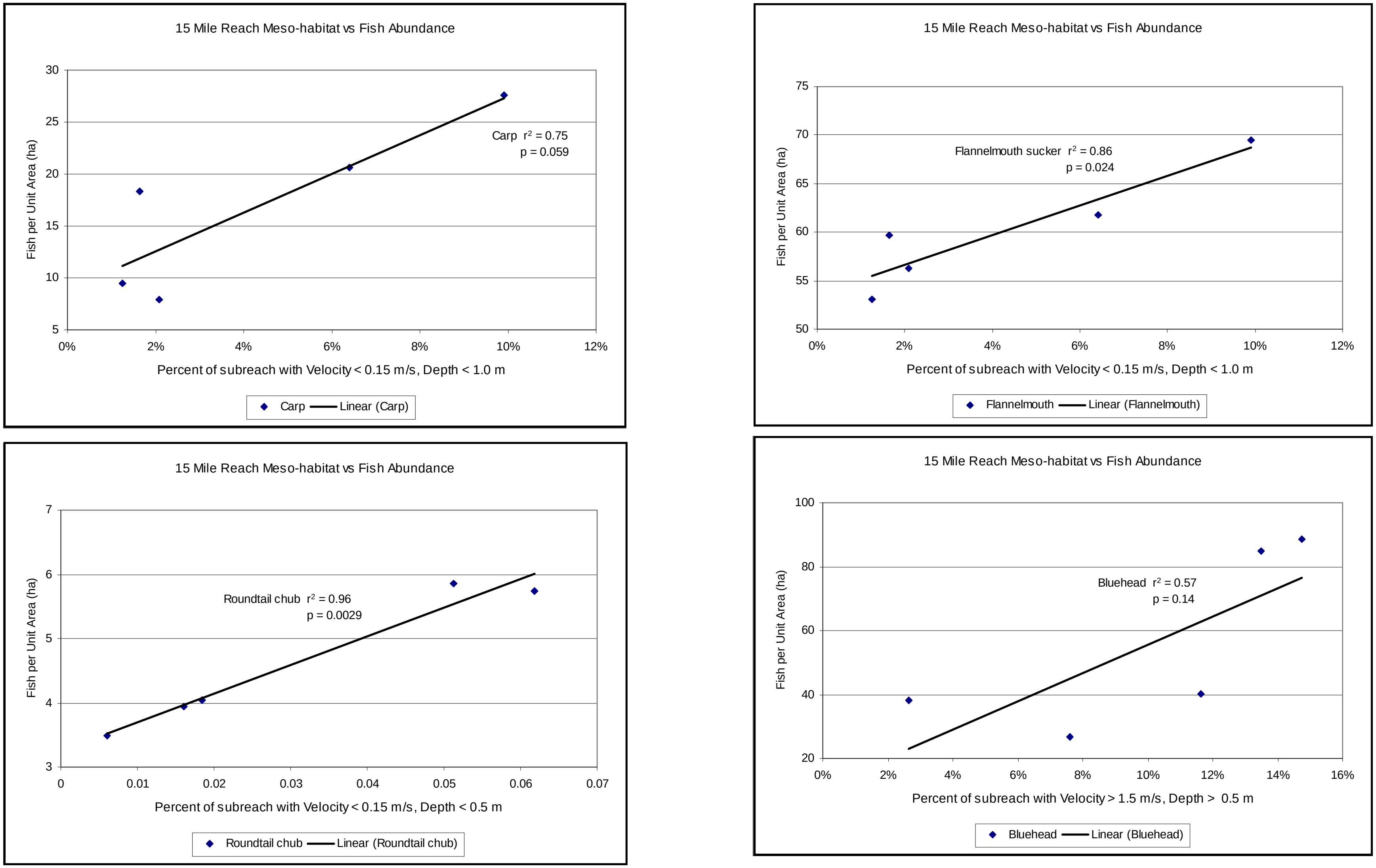


Figure 28: Correlations between meso-habitat availability and number of fish per unit area on the 15 Mile reach.

Table 5: Duffy Tunnel meso-habitat types based on depth.

Habitat Types	Depth (m)	Velocity (m/s)
Wet	0.01-.02	< 0.6
Shallow	0.2-0.4	< 0.6
Moderately Shallow	0.4-0.6	< 0.6
Moderate	0.6-0.8	< 0.6
Deep	0.8-1.0	< 0.6
Deeper	1.0-1.3	< 0.6
Deeper Yet	1.3-1.6	< 0.6
Quite Deep	1.6-1.9	< 0.6
Very Deep	>1.9	< 0.6
	All	> 0.6

These criteria were used to define meso-habitat in sub-reaches of the Duffy Tunnel site a second time with the hope that significant relationships may be exposed for other species of fish. Analysis of fish populations and habitat availability defined by this second set of definitions, however, provided no further insight into fish habitat utilization (Figure 27).

On the 15 Mile reach, fish were captured at flows near 50.97 cms (1800 cfs). Figure 28 has four plots of fish caught per unit area vs. percent meso-habitat. Meso-habitat definitions shown in Table 1 were used for the analysis. As Figure 28 shows, some species show significant correlations between meso-habitat availability and fish abundance. Both flannelmouth sucker and roundtail chub (*Gila robusta*) appear to be significantly more common in reaches with slow shallow habitat.

The correlations shown in Figures 26-28 are somewhat expected. People who have caught blueheads can attest that they prefer fast water whereas flannelmouths appear to prefer slower more shallow areas. Of perhaps more interest are correlations between fish presence and metrics of habitat diversity or heterogeneity. Figure 29 shows the number of fish per unit area as a function of habitat diversity, expressed by the Shannon’s Diversity Index. Flannelmouth sucker, common carp (*Cyprinus cardio*), and roundtail chub all appear to prefer habitats with high habitat diversity. As mentioned previously, some species may be more likely to respond to other indices of heterogeneity, such as the distance between habitats of the same type or the interspersion of habitat types. Figure 30 shows the number of fish per unit area plotted against the mean nearest neighbor distance and interspersion and juxtaposition indices. The negative correlations for nearest neighbor distance suggest that those species prefer reaches where habitat units of the same type are in close proximity to one another, whereas the graph of interspersion and juxtaposition suggests that flannelmouth and white sucker prefer reaches where a given habitat type is more likely to border many different habitat types.

3.4 Wetted-perimeter vs. Wetted Area

As stated previously, the CDOW had hoped that this study might provide recommendations similar to those calculated using the wetted perimeter method. To facilitate

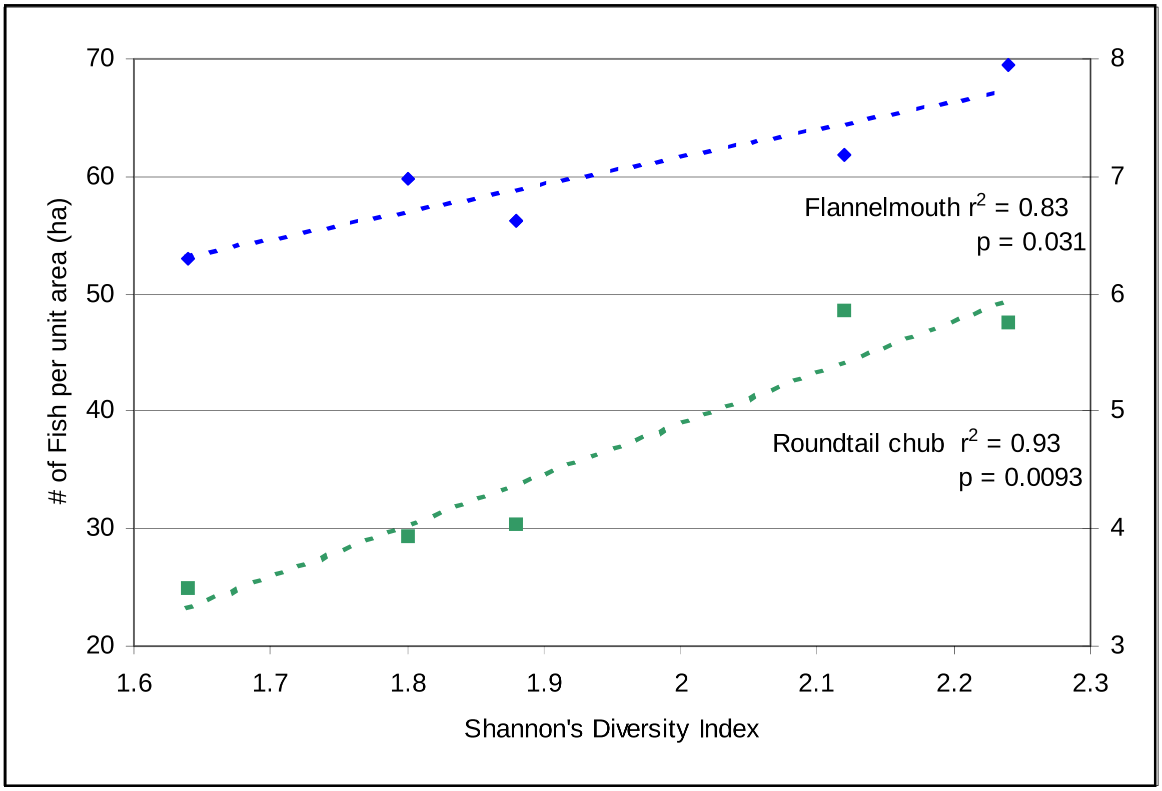
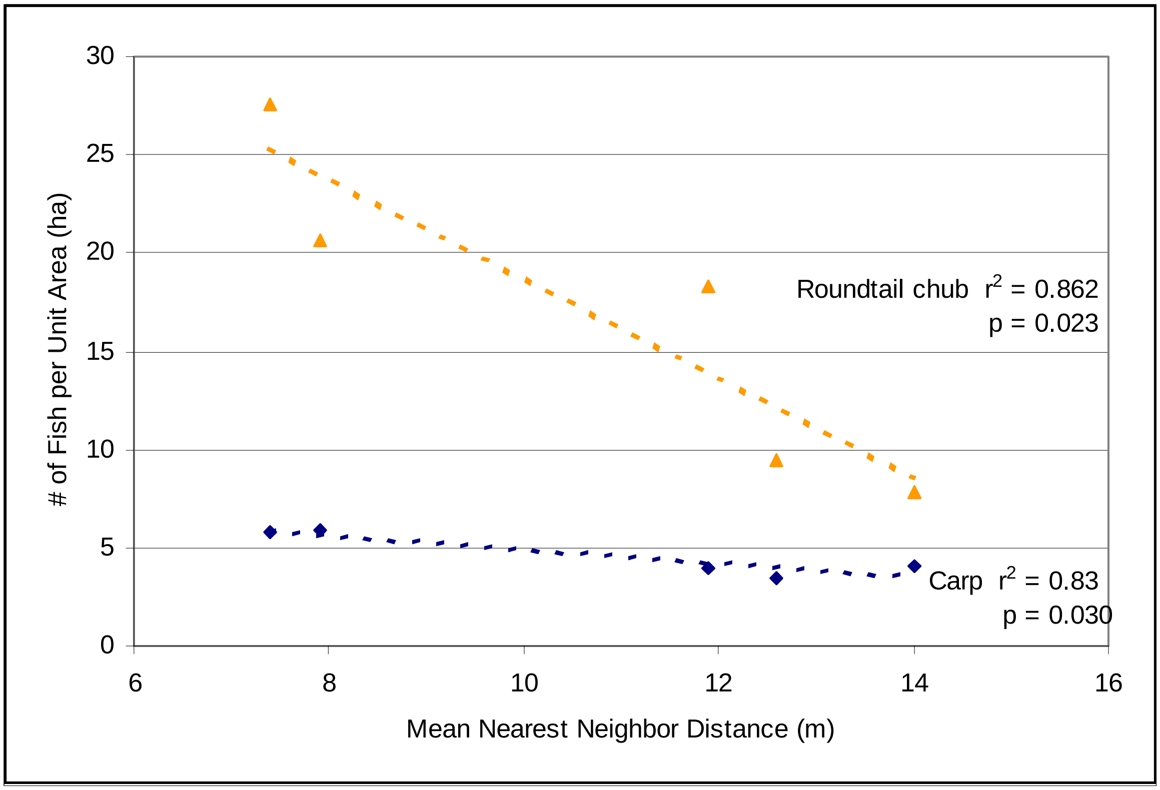


Figure 29: Correlations between habitat diversity and number of fish per unit area on the 15 Mile reach



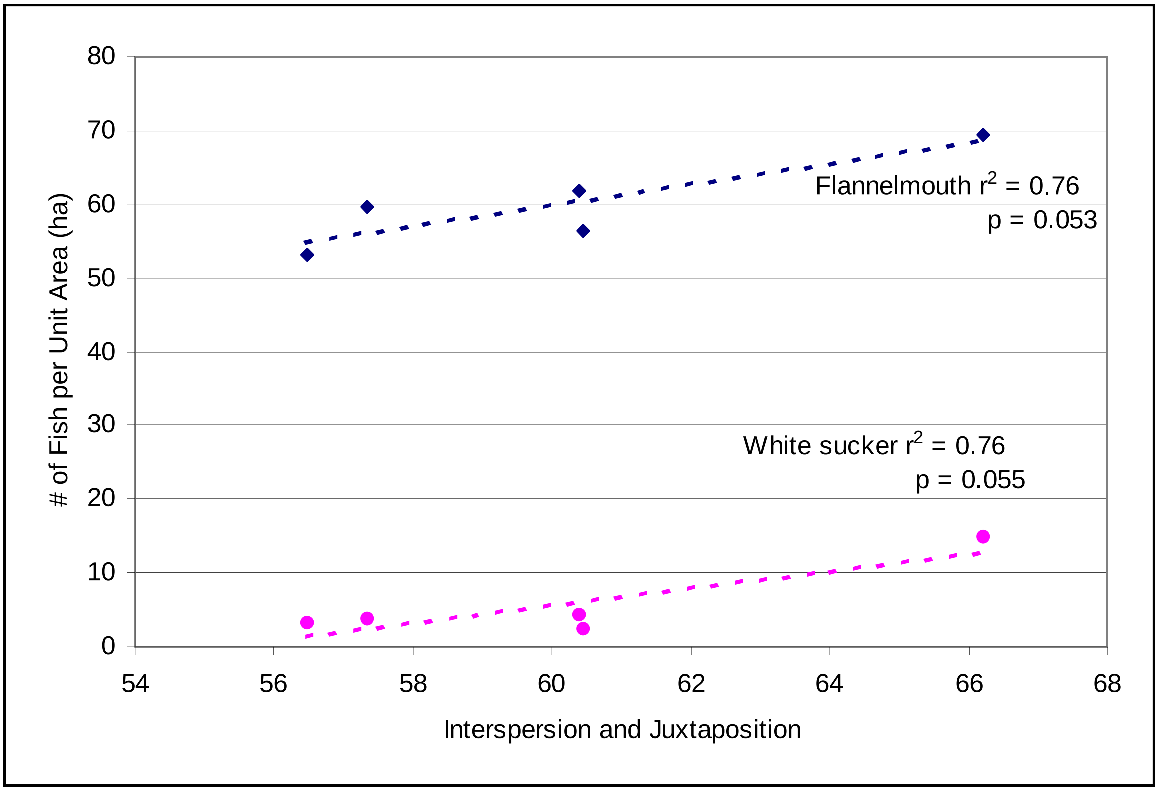
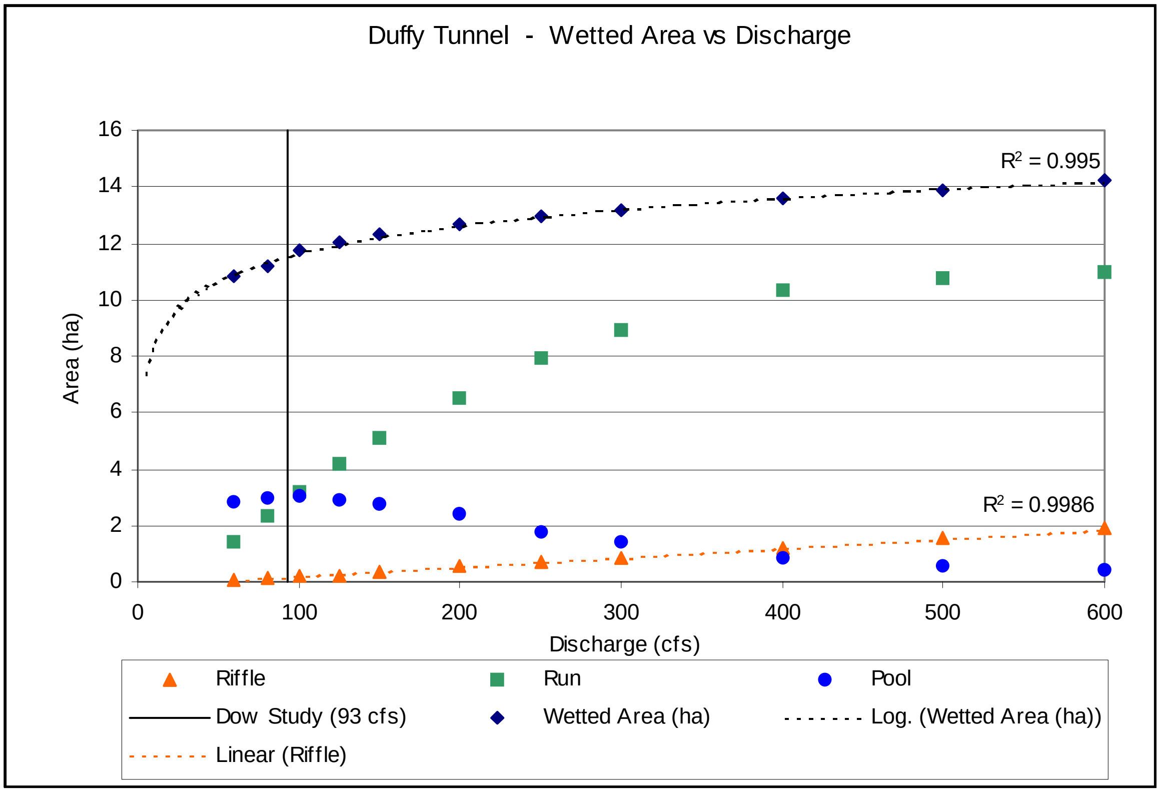


Figure 30: Correlations between measures of habitat heterogeneity and fish abundance.

a comparison, wetted area from the two-dimensional model was plotted as a function of discharge (Figure 30). When wetted area from the whole study reach is evaluated, there appears to be a log-linear relationship between wetted area and discharge.

It is often assumed, however, that riffles are the most sensitive habitat type for fish passage and invertebrate production. As Figure 31 shows, riffle area (defined by this study as those areas having a velocity of 0.15 – 0.6 m/s) grows in a strongly linear relationship with discharge rather than as a log or power function. If these relationships hold true, and the goal is to maximize riffle area for invertebrate production, the inflection point method is not the best methodology for use in making instream flow recommendations.



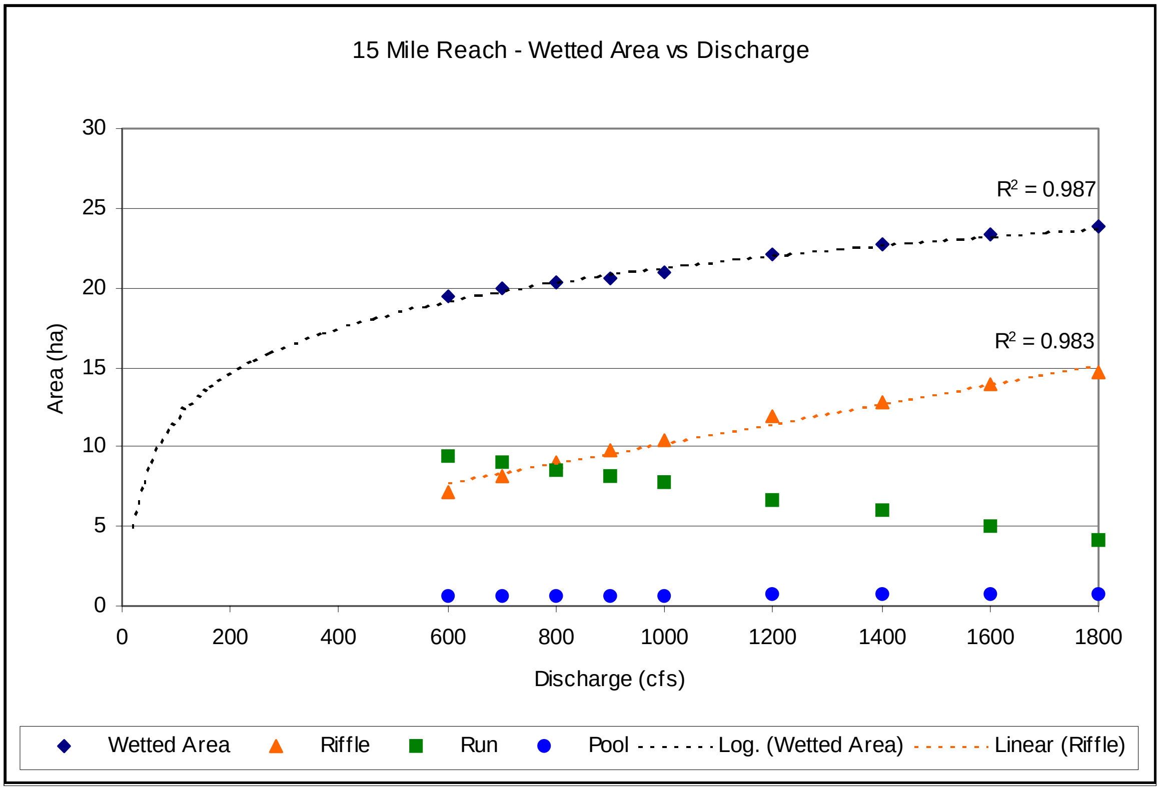


Figure 30: Wetted area as a function of discharge for Duffy Tunnel and the 15 Mile reach.

Chapter IV – DISCUSSION

In this study we have demonstrated that the two-dimensional hydraulic model RMA2 can be used to calculate depth and velocity at a scale relevant to fish (approximately 3 x 5 meter elements). Two-dimensional modeling results can be exported into a geographic information system (GIS) program to create 1 meter grids showing meso-habitat-type based on depth and velocity. For some meso-habitat types, meso-habitat availability, expressed in terms of percent area, is correlated with fish abundance expressed as the number of fish per sub-reach area. These correlations help validate the assumption that fish community structure is significantly influenced by physical habitat availability.

Plots of habitat diversity and wetted area against discharge show that both decline with declining discharge. Plots of wetted area vs. discharge are similar to those found in the 1996 CDOW study and feature an inflection point somewhere near 93 cfs. Plots of habitat diversity vs. discharge, however, show that habitat diversity is maximized as a function of discharge at flows closer to 180 cfs at the Duffy Tunnel site.

One of the objectives of the study was to model twelve different discharges at each of the two study sites. In the end, only 11 discharges were modeled at the Duffy Tunnel site (600 – 60 cfs) and the 15 Mile reach was limited to 10 discharges (1800 – 600 cfs). Two-dimensional hydraulic modeling with RMA2 proved significantly more difficult than originally hoped and problems related to wetting and drying and model stability required that the number of model runs be reduced in order to finish the study in a reasonable amount of time. Additionally, although the Duffy Tunnel runs all use the same finite element mesh with all elements enabled, some of the discharges modeled on the 15 Mile reach required that elements be disabled in order to reach a stable solution with the desired set of boundary conditions. In the worst case, the total area of these elements did not exceed 0.05% of the wetted area of the mesh and probably had no significant impact on the modeling results.

4.1 Data Acquisition

Two different methods were used in this study to gather data for use in creating and calibrating a two-dimensional model. The merits of these technologies go beyond the scope of this particular study but a short discussion is warranted.

As stated in the methodology section, a total station and Marsh McBirney flow meter were used initially to map the channel bed and obtain velocity profiles. The primary advantage of using a total station is that it is relatively cheap, easy to set up and use, and gives the user flexibility to survey points in just those locations where survey data are required. Vertical precision is also generally very high, and in many cases, the instrument will record survey data for later downloading. The only limitation on where points can be recorded is that there must be line-of-sight between the instrument and the location to be recorded, and a person must be able to stand in the survey location for a short amount of time in order to get a fix on distance or calculate velocity. This limits the riverine application to shallow rivers that can be waded or where a boat can be secured so that a pole can be held steady on the river bottom. The ability to map large spatial domains is also limited by the number of points that can be recorded in a given day. With a crew of two, it would be reasonably difficult to survey more than 600 points in a given day. On sections of river that are too deep to easily wade this number is dramatically decreased.

The second method that was used to gather bathymetric data was the use of a GPS, boat, sonar, and ADP. The primary advantage of this method is that it allows the user to gather a very large amount of data in a very short amount of time with little manpower.

Disadvantages of this system include the relatively large expense and difficulty in set up and operation. This system has the additional problems of needing good line-of-sight to at least four GPS satellites to get a fix (which is generally not a problem unless you are working in a confined canyon or in a wooded area) and that there is a minimum depth requirement for boat operation. In shallow areas with swift currents, boat operation may not be possible without serious risk to equipment and crew. This problem may be resolved, however, by using the GPS as a land survey tool and recording points by hand. In this mode the GPS is used like a total station survey rod thereby allowing the user flexibility in determining where survey points are captured.

In general I would advocate the use of the GPS, boat, and sonar method where practical when trying to map large spatial domains. The quality of the data and the speed in which they can be acquired easily outweigh the limitations. Practicability in this case is dictated by ability to gain access to the equipment, receive GPS satellite data, and safely operate a boat over the domain to be mapped.

4.2 RMA2

RMA2 is just one of the two-dimensional hydraulic models available to the public and was used because it is relatively mature and is considered to be relatively stable. As with any study, unexpected problems were encountered during the modeling process. Some unexpected yet significant limitations to modeling a complex riverine environment over a large spatial domain with RMA2 are that: 1) the modeler is almost required to have some knowledge of the hydraulics over the range of flows to be modeled in order create a stable finite element mesh capable of replicating known channel hydraulics, 2) nodes at inflow and outflow boundaries cannot become dry, which may result in the need to create artificial inflow and outflow boundaries, 3) when using RMA2 to model low flows, the use of wetting and drying can be a significant problem and requires the user to predict where elements will become dry and create a mesh specifically adapted to reduce instabilities created by the wetting and drying process, and 4) computational time may be considerable. Where a 1D model, such as HEC-RAS, with several hundred cross sections, will generally take no more than a minute to run, a finite element mesh with 10,000 elements such as the Duffy Tunnel model may take days to weeks to run on a PC with a 500MHz processor (and 256MB of ram) and may require several modifications to reach a stable solution.

These are not the only limitations to the use of RMA2, but are rather a short list of those problems that were significant and came as somewhat of a surprise. The modeling experience also provided some insight for future projects. Mesh generation is an important step in the modeling process and experience showed that the time required for modeling a simulation did not grow linearly with the number of elements; but grew instead as an exponential function. This was largely because the amount of time spent on failed runs. Experience suggests that the modeling process may have been easier if the number of elements had been reduced, especially on the 15 Mile reach model. In general, the Duffy Tunnel model was easier to run because it was smaller. The 15 Mile reach model had more elements than were required and should have had larger average nodal spacing.

Modeling over large spatial domains will probably remain necessary if patterns of habitat use at the meso-habitat scale are to be observed. The following suggestions may reduce the time required for future modeling efforts. First, when modeling over a large range of discharges, where hydraulic conditions are likely to vary significantly, consider using multiple meshes for different ranges of flows and hydraulic conditions. Although the time required to create a finite element mesh can be significant, trying to define one mesh that will be stable under a wide range of hydraulic conditions will generally require very fine meshes. Second, the size of elements should be scaled to match the hydraulic conditions.

Where flow is generally uniform, a reduced number of large elements should be used. In areas of flow separation or where wetting and drying are likely to occur, smaller elements should be used. Third, consider breaking long reaches into smaller subreaches. This last suggestion must be done carefully because models should be started and ended in areas where hydraulics are simple, and areas at the beginning and end of the model are more likely to exhibit inaccurate flow patterns.

4.4 Habitat

Results suggest that meso-habitat availability changes with discharge and that local abundance of fish larger than 15cm is significantly correlated with meso-habitat availability for some species. Moreover, the local abundance for some adult species is significantly correlated with metrics of habitat heterogeneity at the meso-habitat scale. Assuming that these relationships are real, one could expect fish to move between subreaches as discharge and habitat availability/heterogeneity change to locate areas of maximum habitat availability/heterogeneity. This is clearly a question that will need to be answered by future research. As this was only a pilot study, fish community composition was only available at one discharge for each of the study sites. If it can be shown that fish populations are correlated with habitat availability/heterogeneity over space and time, the value of these findings will be increased significantly.

Another question that is raised by this study relates to the lack of correlations between fish abundance and habitat availability/heterogeneity for most species of fish at the Duffy Tunnel site. Many reasons for this are possible, including the possibility that no such correlations exist. Assuming that correlations do exist, the scale at which fish populations and meso-habitat were mapped is the most likely reason that the relationships were not observed in this study.

An implicit assumption in this study was that fish move between subreaches based on habitat characterisitics and that subreach. To keep fish from moving based on the presence of shocking activity, physiographic boundaries used for delineating subreaches should have some cost associated with moving between them. At the 15 Mile reach site, riffles were used to break up reaches. Riffles represent obvious physiographic boundaries for fish because it requires energy to cross the boundary and may represent a real danger to predation from above. As such, it is unlikely that local abundance in a given sub-reach will change appreciably over the time span that shocking is occurring.

At the Duffy Tunnel site, the subreaches were more or less artificially delineated because the modeled reach only included 2.5 riffle/run sequences. The habitat units that were chosen probably did not represent real boundaries within which local abundance might be relatively stable.

Cover was not addressed at all in this study and yet can be a significant component of physical habitat. Cover was not included because of the relative lack of cover at the study sites and because cover was never mapped. At the Duffy Tunnel site, however, proximity to cover may be a key predictor of habitat use for many species. As a suggestion for future work, cover could be mapped at the Duffy Tunnel site and incorporated into the meso-habitat definitions. Analysis using these new definitions might provide additional insight into the use habitat preferences of species on the Yampa River.

The relationships between diversity and community composition are still currently theoretical, although this study does provide evidence that such relationships do exist. Many people, including the creators of IFIM, agree that one of the greatest values of using two-dimensional flow models for making instream flow recommendations on warmwater rivers is that these models are spatially explicit and permit the examination of patterns of meso-habitat use at community level. The continued use of these models combined with increased knowledge of patterns of fish movement within these modeled reaches over a range of discharges will likely provide insight into the processes which may be limiting to fish existence.

4.5 Conclusion

Two-dimensional hydraulic modeling represents a significant improvement in the ability to map features related to physical habitat, specifically depth-averaged velocity and depth. The additional time and financial resources needed for this type of modeling are currently keeping it from being used in a large number of projects, and will continue to keep it out of mainstream use for some time.

Two-dimensional modeling is orders of magnitude more difficult than 1-D modeling, especially when trying to model over large spatial domains. Additionally, there are still problems associated with incorporating biology into the results. The ability of a 2-D model to describe the physical domain is much greater than our ability to describe the communities that inhabit that domain and yet falls far short of being able to describe the suite of physical processes that might influence the composition of those communities. These processes include long-term changes in hydrologic regime, habitat modification, groundwater inputs, nutrient inputs, changes in the local food web, turbidity, or temperature.

The results of this study should be viewed with caution and with consideration for the fact that the fish data used here represent only a pilot study. With this said, it is clear that if the goal of a given project is to gain new insights into the role that hydraulic attributes play in structuring aquatic communities, use of 2, or 3-dimensional modeling may not only be warranted, but may in fact be necessary.

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