EFFECTS OF STREAMFLOW VARIATION ON SMALLMOUTH BASS HABITAT IN AN ALLUVIAL STREAM

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CHAPTER I.

INTRODUCTION

This thesis is composed of one manuscript written in the format suitable for submission to the North American Journal of Fisheries Management. Chapter I is an introduction to the rest of the thesis. The manuscript is as follows; Chapter II, "Effects of streamflow variation on smallmouth bass habitat in an alluvial stream."

CHAPTER II.

EFFECTS OF STREAMFLOW VARIATION ON SMALLMOUTH BASS HABITAT IN AN ALLUVIAL STREAM

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Abstract

We used Physical HABitat SIMulation system (PHABSIM) to evaluate effects of stream discharge variation on smallmouth bass Micropterus dolomieu habitat in an alluvial stream, Baron Fork of the Illinois River, Oklahoma during 1999 and 2000. We assessed how streamflow-related changes in channel shape and structure in an alluvial stream affected quality, quantity, availability, and spatial distribution of juvenile and adult smallmouth bass habitat. Specifically, we (1) tested reliability of juvenile and adult smallmouth bass Habitat Suitability Criteria (HSC), (2) evaluated changes in available smallmouth bass habitat between years, and (3) compared predicted smallmouth bass Weighted Usable Area (WUA) with observed WUA measured the following year. From PHABSIM analysis, we found that both juvenile and adult smallmouth bass habitat were differentially affected by intra- and interannual discharge fluctuations. Maximum WUA for juveniles and adults occurred at discharges of 1.8 m^3/s and 2.3 m^3/s, respectively, and WUA dropped off sharply for both groups at lesser discharges. Weighted usable area for juvenile and adult smallmouth bass declined during the summer low-flow period (August-October). Habitat suitability criteria for juvenile smallmouth bass were inconsistent between years, but HSC for adult smallmouth bass were consistent with observed habitat relationships ($P < 0.01$). For most microhabitat variables habitat availability was similar between years (68.2%). These findings indicate that changes in habitat availability should be taken into account when evaluating effects of stream discharge variation in alluvial streams. Our findings also suggest that annual

variation in habitat availability affect predictive ability of habitat models for juvenile smallmouth bass more than those for adult smallmouth bass.

Introduction

Distribution and abundance of stream fishes are strongly influenced by habitat structure. Physical habitat features such as cover type, substrate size, and velocity are associated with abundances of stream fishes (Hubert and Rahel 1989). Ultimately, stream-fish habitat is affected by fluvial and geomorphic processes controlled by climate, geology, land use, and basin physiography (Knighton 1998). Rabeni and Jacobson (1993a) documented the influence of stream geomorphology and fluvial processes on centrarchid distribution and abundance in Ozark streams of Missouri. Centrarchid populations were greatest in upstream reaches where gradients were higher and stream valleys were narrower and incised into steep bedrock bluffs. As a result, upstream reaches had more cobble and boulder substrate and less gravel and sand than downstream reaches, making upstream habitats more favorable for centrarchids. Smallmouth bass Micropterus dolomieu were associated with different types of pool habitats (i.e., bluff, lateral, obstruction, mid-channel, and backwater) depending on time of day, year, and fish size (Rabeni and Jacobson 1993b).

Magnitude of stream discharge and flow regime influence channel form (Knighton 1998) and fluvial processes (i.e., erosion and deposition) in alluvial streams. Unregulated alluvial river systems in temperate regions are subject to changes in channel-bed mobility, deposition, and riparian stability during extreme stream discharge events (McBain and Trush 1997). Extreme storm and flood events in alluvial systems, which typically occur at intervals of 50 to 200 years, scour and widen the stream channel (Webster and D'Angelo 1997). Poff and

Allan (1995) found that fish assemblages having higher proportions of resource generalists tended to be associated with hydrologically variable streams, whereas assemblages associated with stable habitats were characterized by higher proportions of specialist species.

One of the most widely used methods of assessing aquatic habitat in relation to change in stream discharge is the Instream Flow Incremental Methodology (IFIM; Reiser, et al. 1989; Armour and Taylor 1991). Instream Flow Incremental Methodology has been used to evaluate a variety of instream flow problems, from simple diversions of stream channel to complex storage and release schemes involving hydropeaking schedules, pump-storage, and a network of interconnected reservoirs (Stalnaker et al. 1995). Incremental instream flow techniques quantify aquatic habitats beneficial to fish and other aquatic organisms as a function of stream discharge (Stalnaker et al. 1995). Knowledge about conditions providing favorable or unfavorable habitat for a species is necessary for successful implementation of the methodology. Overall, IFIM has been used as a basis for protecting desired instream values and promoting compromises among conflicting water interests (Cavendish and Duncan 1986).

Whereas IFIM is a general instream flow problem-solving approach, Physical HABitat SIMulation system (PHABSIM) is a specific model within IFIM that was designed to calculate amount of available habitat for a species at different stream discharges (Stalnaker et al. 1995). The purpose of PHABSIM is to develop functional relationships (i.e., weighted usable area) between stream discharge and physical microhabitat using (1) channel structure, (2) hydraulic simulation, and (3) Habitat Suitability Criteria (HSC; Bovee 1986). At any particular discharge, each stream cell has a unique combination of depth, velocity, substrate, and cover. When discharges are simulated in the hydraulics program of PHABSIM, depths and velocities in cells often change with discharge. To translate the changes into an estimate of available habitat, one must determine what depths and velocities, types of cover, and substrata are important to the target species. Preferences of organisms for hydraulic and structural characteristics of their microhabitats are collectively referred to as habitat suitability criteria. Physical attributes of each stream cell can be compared with HSC to determine weighted value of the cell as microhabitat for a particular organism. This value can then be multiplied by surface area of the cell to obtain Weighted Usable Area (WUA; Bovee 1986). Relationships between stream discharge, variation in fish habitat, and fish population dynamics have been investigated with PHABSIM for several species, including rainbow Oncorhynchus mykiss and brown Salmo trutta trout in Colorado streams (Nehring and Anderson 1993), Chinook salmon Oncorhynchus tshawytscha in Trinity River, California (Bartholow et al. 1993), and smallmouth bass and rock bass Ambloplites rupestrus in Huron River, Michigan (Bovee et al. 1994).

Smallmouth bass have habitat requirements that are either directly or indirectly associated with feeding, spawning, life stage, predator avoidance, and extent and availability of these habitats varies in relation to changing stream discharges. It is commonly assumed that low-flow events are the principal cause of habitat bottlenecks in streams (Bovee et al. 1994), and extreme low-flow events can reduce fish populations to well below carrying capacity of the environment (Stalnaker et al. 1995). Adult populations are frequently determined by recruitment success, which is highly correlated with amount of habitat available for early life stages (Stalnaker et al. 1995). By analyzing habitat availability, Bovee et al. (1994) found that abundance of yearling smallmouth bass was associated with summertime amount of nighttime microhabitat available for young-of-year. Bovee et al. (1994) also found that habitat types not directly utilized by a fish species (such as macroinvertebrate habitat as it affects food supply for fish) may be as important as directly used habitats. Critical habitat associations, therefore, may affect fish populations during periods of low habitat availability.

The IFIM was originally developed for use in coldwater streams in western United States, but it has also been used in a variety of warmwater streams. Warmwater streams exhibit a wide range of hydraulic and geomorphic properties and, therefore, require different instream flow assessment methods. Orth and Maughan (1982) evaluated IFIM in a bedrock-dominated stream in the Ouchita Mountains of southeastern Oklahoma where streams are typically runoff dependent and exhibit substantial loss of habitat in summer. When discharges were near zero, there was a direct relationship between standing stock and weighted usable area (WUA; Orth and Maughan 1982). Leonard and Orth (1988) examined a variety of warmwater stream types in Virginia and identified fish assemblage-habitat associations by using PHABSIM. They identified four habitat-use guilds and recommended discharges based on these guilds. The resulting instream flow recommendations were similar to those based on the Montana and wetted-perimeter method for low-flow season only (Leonard and Orth 1988). Osborne et al. (1988) found that water-surface profile model used in PHABSIM was inadequate at simulating low-flow habitat conditions in low-gradient, fine substrate warmwater streams in Illinois. Similar instream flow methods have, however, been used effectively in Ozark streams in Arkansas (Filipek et al. 1987; Mays et al. 1990). These stream systems closely resemble Ozark streams of Oklahoma, including Baron Fork of the Illinois River.

Instream Flow Incremental Methodology and its models have been criticized by some and defended by others. Mathur et al. (1985) and Mathur (1986) stated that failure of IFIM to produce a positive linear relationship between WUA and biomass of fish violates a basic assumption of the methodology. In response, Orth and Maughan (1986) pointed out that evidence to support positive WUA-biomass relationships exists for periods when habitat is extremely limited, such as summer low-flow periods. They argued that even though positive WUA-biomass relationships may not always occur, use of WUA as an index of potential fish biomass is acceptable because abundance may be complicated by other factors including time lags in habitat availability and interspecific competition. Modeling with PHABSIM allows habitat availability to be predicted on the basis of historical stream discharges. To make accurate predictions and forecasts with PHABSIM, Gore and Nestler (1988) stated that modeled habitat needs to remain stable during the study period as well as into the future. Also, WUA-discharge curves are more accurate if the time frame that PHABSIM data are collected in can be minimized (Moyle and Baltz 1985).

Smallmouth bass have been a target species for several IFIM studies. In Oklahoma, the species is an important sport fish, and several studies have examined life history characteristics of stream populations, including the one in Baron Fork of the Illinois River. Stark and Zale (1991) concluded that large, inconsistent year classes and high densities of smallmouth bass characterized Baron Fork smallmouth bass. Fish grew rapidly until age two, after which growth declined. They speculated that older, larger individuals might have emigrated downstream (e.g., Illinois River, Lake Tenkiller) where habitat requirements were better met by the larger bodies of water. However, Balkenbush and Fisher (1999) found that growth rates for older smallmouth bass in Baron Fork were higher than reported in the study by Stark and Zale (1991).

We assessed how streamflow-related changes in channel shape and structure in an alluvial stream affected habitat availability and spatial distribution of smallmouth bass habitat. We modeled juvenile and adult smallmouth bass habitat in Baron Fork in summer and fall 1999 with PHABSIM and verified model results and tested assumptions of PHABSIM with data collected in summer and fall 2000. Specifically, we (1) tested reliability of Habitat Suitability Criteria (HSC) for juvenile and adult smallmouth bass, (2) evaluated changes in available smallmouth bass habitat between years, and (3) compared predicted WUA for smallmouth bass with the estimated value in the following year.

Methods

Study Area -- Baron Fork is a tributary of the Illinois River that originates in northwest Arkansas and discharges through Adair and Cherokee counties in Oklahoma where it joins Illinois River above Lake Tenkiller. Like many Ozark streams, the Baron Fork drainage is underlain by an extensive karst system that supports large springs (Rabeni and Jacobson 1993a). Baron Fork is one of Oklahoma's few remaining free-flowing streams and has been designated as a scenic river (OKWRB 1990). Channel substrate in the stream is mostly chert gravel derived from limestone and dolomite bedrock. Historically, Ozark streams deposited mostly sand and clay particles on the flood plain, but anthropogenic activities such as logging, overgrazing, and burning accelerated rates of erosion and gravel deposition in Ozark streams (Rabeni and Jacobson 1993a).

We defined our study segment boundaries by first constructing a longitudinal profile of stream gradient from measurements on USGS 7.5 minute topographic maps. We selected a 21.5-km segment with relatively homogenous gradient that included Adair County Rural Water District #5 municipal water-supply intake (Figure 1). The upper boundary of the segment was located at Christie Bridge on County Road N4669 in Adair County, Oklahoma. The lower boundary was just above Eldon Bridge on Highway 51 in Cherokee County, Oklahoma.

Hydrologic Analysis -- Historical daily mean discharge values from the USGS stream gage station located at Eldon Bridge (station number 07197000) were downloaded from the USGS Internet site (http://csdokokl.ok.cr.usgs.gov). These data were used to verify our estimates of discharge during field sampling. They were also analyzed with Indicators of Hydrologic Alteration software (IHA, The Nature Conservancy) to identify 25th, 50^{th}, and 75^{th} percentile monthly stream discharges. For this study, we operationally defined monthly median (50^{th} percentile) of the distribution of discharge for the period of record discharge as a normal year, lower 25^{th} percentile as a dry year, and upper 75^{th} percentile as a wet year (Fisher and Remshardt 2000).

Physical Habitat Measurements -- To map and measure habitat characteristics within the study segment, we first acquired digital orthophotoquad (DOQ) topographic maps of Baron Fork basin from the Spatial and Environmental Information Clearinghouse Internet site (www.seic.okstate.edu; SEIC 1999). Digital orthophotoquad maps were formatted for use in ArcView GIS software. These maps, along with field observations enabled us to evaluate stream channel and floodplain conditions. We used the classification system devised by Hawkins et al. (1993) to visually identify and classify geomorphic channel units (GCUs) while canoeing in the stream in May 1999 (Appendix A). For the purpose of this study, we refer to GCUs as mesohabitats. We then digitized mesohabitats onto a base map of the stream using Arcview GIS software. Arcview GIS was used to map and quantify area and length of each mesohabitat type. Mesohabitats were used to stratify sites for fish sampling and to quantify microhabitat characteristics for PHABSIM modeling (Bovee 1994) in three sampling sites (Figure 1).

Stream discharge and microhabitat channel features were measured at all three sites in the study segment. Establishing study sites consisted of: (1) defining lower and upper site boundaries, (2) subdividing the site into stream cells with transects, (3) establishing horizontal control, and (4) establishing vertical control. Mesohabitat types were sampled proportionately based on the May 1999 survey of the entire stream segment.

Discharge and microhabitat data were collected from June through August of 1999 following procedures described by Bovee (1994). We established site boundaries and elevations of all three study sites by surveying each study site with a Topcon AT-G7 autolevel and stadia rod. The minimum horizontal data that is required in PHABSIM is distance between transects, and relative length of stream cells defining a site. We obtained these data by measuring distances between left-bank and right-bank of one transect with another or to an established benchmark. Compass bearings to at least two different established points were determined in order to recreate transects for subsequent mapping and later sampling. Distances less than or equal to 120 m were measured with a steel tape. For distances over 120 m, we used the level and stadia rod. Distances between the level and stadia rod were estimated by subtracting the lower stadia reading from the upper stadia reading and multiplying that number by 100. This gave us an estimate in feet that was converted to meters. A compass located on the level allowed us to determine bearing to transect points or benchmarks.

Vertical measurements of a site were used to calculate hydraulic slopes, establish benchmarks, and create site maps to use in modeling calculations of PHABSIM. All elevations in a site were referenced to a common datum. By installing permanent benchmarks at each site and relating their elevations by differential leveling. Benchmarks allow a backsight to a known elevation from anywhere in each site. The downstream-most benchmark at each site was arbitrarily set at 100.00 meters. After the last benchmark in each site was surveyed, the survey was conducted in reverse to check for errors in elevations, a process termed closing the loop. By defining permanent benchmarks and marking their location with a global positioning system (GPS) receiver (Trimble GeoExplorer II), we were able to return to our sites and re-measure transects at different discharges.

Channel cross-sections were described by a series of horizontal and vertical coordinates. Channel profile data associated with measurements along each transect included a horizontal and vertical distance from a known datum to the nearest 0.1 m, water surface elevation to the nearest 0.01 m, and descriptions of cover and substrate. Cover and substrate data were recorded in abbreviated form and transformed into channel index codes during data entry (Appendix B). Substrata were classified with a USGS gravelometer. Depth and velocity measurements were taken from 62 transects (31, 26, and 5 at sites 1,2, and 3, respectively) with a 1.5-meter wading rod attached to a flowmeter (Marsh-McBirney Model 2000) in 1999. For depths less than 0.75 m, a single velocity measurement was taken (40-second interval) at 60% of depth. For depths over

0.75 m, two measurements were taken, one each at 20% and 80% of total depth. These two velocity readings were then averaged to obtain a single measurement. Readings at the downstream-most transect at each site were taken on different days and discharges to obtain a stage-discharge relationship for each site. Substrate and cover variables were classified based on classes modified from Bovee (1986).

Smallmouth Bass Sampling and HSC Development -- Prepositioned areal electrofishers (PAEs, Fisher and Brown 1993) were used to collect smallmouth bass at randomly selected sites throughout the study segment in 1999. A boat-mounted electrofisher was used to sample fish in depths over 1.5 m. We used the double diamond sampling pattern described by Bovee et al. (1994) to minimize disturbance between PAE electrodes. Transects were placed at least 30-50 m apart with 2-5 PAE electrodes per transect. The purpose of pre-positioning the electrode is to minimize disturbance associated with a constantly moving electrical field (e.g., mobile backpack electrofisher). Each PAE electrode was positioned, left undisturbed for at least 10 minutes, and then energized. As soon as the electrode was energized, a team of two dipnetters immediately approached the electrode and netted immobilized fish. After sampling, captured fish were held in an instream pen for further processing. All smallmouth were counted, measured, and weighed in the field and returned to the stream. Next, microhabitat variables (depth, velocity, substrate, and cover) were measured and recorded for each PAE location.

In September and October of 2000, we observed smallmouth bass by snorkeling in the study sites. Following procedures described by Li (1988), observed fish locations were marked with a lead weight attached to a float and microhabitat variables (depth, velocity, substrate, cover) were measured at their locations. Fish were classified as either being juvenile or adult by comparing lengths with a hand-held ruler marked at 115 mm. (≤ 115 mm for juveniles, > 115 mm for adults). These age criteria were based on an analysis of length frequency distributions of smallmouth bass collected during September and October of 1999 (Figure 2). For both years, locations of each sampling point were determined by distance and compass bearing measurements from GPS benchmarks.

Habitat suitability criteria were constructed for both juvenile and adult smallmouth bass for depth, velocity, substrate, and cover based on 1999 field samples from Baron Fork. For depth and velocity curves, data were combined into 5-cm (cm/sec) intervals to simplify the analysis. Although fish can detect changes in velocity as small as one cm/s, histograms created at this level of accuracy frequently result in irregular distributions which are usually a result of inadequate sample size or microhabitat measurement errors (depth and velocity measurements are precise to only about 3 cm and 3 cm/s, respectively) and are not reflective of discriminatory behavior by fish (Bovee 1986). Substrate and cover variables were combined into one variable, termed channel index (CI) for entry into PHABSIM. These types of structural features do not change directly and immediately as a function of discharge, and are restricted to a single entry in

PHABSIM. All electrofishing samples were used to estimate habitat availability, which was compared with smallmouth bass collections to create HSC.

For each microhabitat variable (depth, velocity, CI), HSC were constructed for juvenile and adult smallmouth bass using non-parametric tolerance limits (Somerville 1958; Bovee 1986). Non-parametric tolerance limits are listed in tables that generally contain pairs of numbers representing the smallest and largest ordered value in a sample. These values define the limits that a specified proportion of the population will be between at a given confidence level (Remington and Schork 1970). These non-parametric tolerance limits were applied to preference criteria developed from microhabitat availability and use data collected from electrofishing samples. For small sample sizes less than 100, non-parametric tolerance limits provide better estimates of actual habitat preferences than nonlinear regression techniques for developing HSC (Bovee 1986). Next, habitat preferences were classified into three ranges of quality (Bovee 1994): optimal, usable, and suitable. The optimal range contained the central 50% of observations and was given a normalized suitability index (NSI) of 1.0 following the formula (NSI = 2(1-P)) where P is the proportion of the population under the curve (i.e., 50%, 75%, and 95% ranges). The usable range encompassed the central 75% (NSI = 0.5) of observations and the broadest variable. The suitable range contained locations within the 95% (NSI = 0.1) range (Bovee 1994). These suitability curves were then entered into PHABSIM (version beta-2) to determine habitat quality and quantity for each microhabitat simulation run.

PHABSIM Modeling -- We used PHABSIM programs to model smallmouth bass habitat at different stream discharges as described by Milhous et al. (1989). Habitat was modeled with measured discharges to predict hydraulic conditions at unmeasured discharges with PHABSIM. There are several different techniques to model stream discharge within PHABSIM. Water surface elevations were estimated for simulated discharges using a combination of the stage-discharge relationship (STGQ) and either Manning's equation (MANSQ) or Water Surface Profile (WSP). The STGQ was used to model water surface elevation at the downstream most transect. After an appropriate STGQ was calibrated, MANSQ was used for transects that were not in pool habitats (e.g., riffles and runs). Use of MANSQ in pools can be problematic because pools are generally affected by a backwater effect created by a riffle or other downstream control. Manning's equation requires adjusting a conveyance factor variable (beta) to minimize error between observed and simulated discharges. Each transect is considered independent of other transects and is modeled as such. An overall average beta value is calculated first, and then simulated water surface elevations at each transect are compared individually to corresponding observed water-surface elevations. Beta values are again adjusted to minimize differences between water surface elevations. In pool transects, WSP was used because it more closely simulates discharges in pool habitats. The WSP is similar to MANSQ, but WSP assumes that each transect is affected by a riffle or other downstream hydraulic control that effectively creates a backwater effect. All transects in a site must be tied together to a common benchmark to effectively use this method.

The process of using WSP model involves selecting coefficient values that best fit water-surface elevations at each transect for the highest calibration discharge and then applying this coefficient to other discharges.

Weighted usable area estimates for each site were calculated for simulated discharges between 0.28 m^3/s (10 ft^3/s) and 8.5 m^3/s (300 ft^3/s). Weighted usable area values for each site were then weighted by the proportional length of the site to obtain a single WUA estimate for each discharge and life stage of smallmouth bass. The point at which maximum WUA occurred was considered the optimum discharge for subsequent microhabitat simulations. Overall WUA values for juvenile and adult smallmouth bass were then compared with historic discharge values to estimate historic habitat availability.

Verification Tests – We used GIS to compare predicted cell habitat quality (optimal, usable, suitable) with actual fish locations. A similar approach was used by Thomas and Bovee (1993) to test transferability of HSC between streams. Composite suitabilities were calculated for each cell, using HSC developed from 1999 sampling. Each cell was classified based on the variable with the lowest suitability class. For example, composite suitability for a cell was classified as optimum if individual suitabilities for depth, velocity, substrate, and cover were all optimal. A cell was classified as usable if any variable was classified as usable and all other variables were classified as usable or higher (suitable or optimal). A cell was classified as suitable if any variable was classified as suitable and all other variables were classified as suitable or optimal. If suitability for any variable was unsuitable, composite suitability for the cell was classified as unsuitable. If HSC developed in one year are transferable to the same stream the next year, even after significant alterations in channel structure due to an extreme flood, then HSC should be considered usable from year to year in that stream. Furthermore, if fish select optimal, usable, or suitable cells more frequently than unsuitable cells, then HSC accurately identify habitat quality. Chi-square tests were used to identify differences in habitat use with significance at alpha = 0.05. Bonferroni corrections were applied to tests within each microhabitat variable in each study site (for example site 1 depth, alpha / 4 = 0.0125 for each individual test).

In 2000, 36 transects (12 in each site) were placed as close to original transects as possible to evaluate changes in microhabitat availability within mesohabitat types and channel structure. Distributions of each microhabitat variable (depth, velocity, substrate, and cover) within each mesohabitat were compared between years with a Kolmogorov-Smirnov two-sample test (SAS PROC NPAR1WAY-EDS; SAS 1988). This test was used to determine if two samples come from identical distributions. The test criterion compared distribution functions from of each continuous (depth and velocity) and discrete (substrate and cover) microhabitat variable for both years to determine maximum numerical difference between them (Steel et al. 1997).

We analyzed change in channel position and structure between 1999 and 2000 with GIS and stream-channel transect data. We overlaid channel boundaries from 1999 and 2000 transect data with GIS to detect changes in channel movement. Stream-channel transect data were analyzed to detect change in channel morphology over time. Two indices, net percent change in area and absolute percent change in area were calculated following methods described by Olson-Rutz and Marlow (1992). Net percent change in area under the transect quantifies net degradation or aggradation of the channel. The absolute percent change in area quantifies cumulative streambed or streambank material movement.

To further analyze habitat stability, we compared WUA values for adult and juvenile smallmouth bass calculated from the 1999 PHABSIM model to observed WUA values calculated from 2000 habitat sampling. Discharge values used to model WUA were taken from the gauging station on Eldon Bridge at the time of sampling in 2000 (1.13, 0.57, and 1.42 cubic m/s for sites 1,2,and 3, respectively). These WUA values were within the range of measured values from 1999 sampling (0.28 - 4.46 cubic m/s). Each WUA observed in 2000 was compared with PHABSIM predicted (1999) values at that discharge with a T-test (alpha = 0.05).

Results

Hydrologic Trends -- Our analysis of historic stream discharge based on a 51-year period of record (1948-1999), revealed a low-flow period from July to November with extreme low-flows occurring in the months of August, September, and October (Figure 3, Table 1). Field data collection occurred during this low-flow period. Discharges recorded during sampling in 1999 and 2000 (0.37-6.70 m^3/s) were near historic median discharges for August, September, and October (Table 1). On 21 June 2000, a record flood event was recorded at the Eldon

Bridge gauging station on Baron Fork. An instantaneous discharge of 1,549.8 m^3/s (54,731 ft^3/s) with a stage height of 8.16-m (26.77-ft) was measured. The previous record, 1432.8 m^3/s (50,600 ft^3/s) with a stage height of 7.90-m (25.93-ft), occurred in 1990.

Physical Habitat Characteristics – We identified 249 individual mesohabitat units in the 21.5-km study segment (total area surveyed 444,193 m^2) distributed as follows: 4% backwater, 23% mid-channel pools, 17% lateral pools, 37% runs, and 20% riffles (Table 2).

Microhabitat characteristics were based on 705 measurements of depth, velocity, substrate and cover at the three sites. In 1999, gravel substrata (small 2-8mm, medium 8-16, and large 16-64) composed 84.8% of all measurements, whereas cobble, boulder, and bedrock substrates accounted for only 8.7% of measurements. Remaining substrata were detritus (0.3%), vegetation (0.3%), clay (0.1%), silt (2.3%), and sand (3.6%). Available cover is generally sparse but can be locally abundant in Baron Fork. Most (90.9%) point measurements did not have cover objects. Of points that did contain some type of cover, most were either rootwad or log formations (7.0%). Other cover types found in lesser amounts were fractured bedrock (0.9%), boulder (0.6%), aquatic vegetation (0.4%), and undercut banks (0.3%). Stream depths ranged from 0.03 m - 2.90 m with an average of 0.71 m. Velocity measurements ranged from 0.00 m/s - 0.96 m/s with an average of 0.12 m/s.

Smallmouth Bass HSC -- A total of 275 smallmouth bass were either collected (1999) or observed (2000) during the study. In 1999, 266 electrofishing samples produced 100 smallmouth bass (36 juveniles, 64 adults). A total of 175 smallmouth bass (79 juveniles, 96 adults) were observed snorkeling in 2000.

Habitat Suitability Criteria for juvenile and adult smallmouth bass in Baron Fork reflected differences in habitat use between size classes (Table 3). Juveniles preferred depths between 35 and 115 cm, velocities between 25-80 cm/s, medium gravel (8-16 mm) substrate, and undercut banks for cover. Adult smallmouth bass preferred depths between 55 and 155 cm, velocities between 10-30 cm/s, large gravel (16-32 mm) substrate, and rootwads for cover. Neither age group used clay, vegetation, or detritus. All cover types (except fractured bedrock) were used by both age groups, except for aquatic vegetation, which was only associated with juveniles.

PHABSIM Modeling – Weighted usable area was greatest at a discharge of 2.32 m^3/s for juveniles and 1.78 m^3/s for adults (Figure 4). Stream discharges simulated between 0.28 m^3/s and 8.50 m^3/s indicated that juveniles had between three and four times more WUA than adults at all simulated discharges. For example, at 2.83 m^3/s, WUA for juveniles and adults was 4076 $m^2/1000$ m and 1049 $m^2/1000$ m WUA, respectively. The corresponding values were 3789 $m^2/1000$ and 1263 $m^2/1000$ at a discharge of 1.42 m^3/s (Figure 4).

Available habitat declined during the low-flow period (August to October) for most years from 1948 to 1999. During these periods, stream discharge was less than 2.1 m^3/s (Table 1) and WUA equaled or fell below the optimum for both juvenile (WUA = 4076 $m^2/1000$ m) and adult smallmouth bass (WUA = 1049 $m^2/1000$ m) during wet (75th percentile), normal (median), and dry (25th

percentile) years (Figure 5). Weighted usable area for the driest month (September) of dry years (25^{th} percentile), declined from that for normal conditions by 36.3% for juveniles and by 34.6% for adults.

Model Verification -- A total of 22,079 m^2 (374 cells) of stream habitat were analyzed to test for smallmouth bass HSC transferability between years. Juvenile smallmouth bass HSC developed from 1999 measurements did not correspond well with fish locations observed in 2000 at all three sites. All cells containing juveniles in 2000 were either suitable (N = 26) or unsuitable (N = 13) (Figures 6-8). Furthermore, chi-square analysis indicated that juveniles did not significantly select suitable cells over unsuitable cells ($\chi^2 = 0.71$, $\underline{P} = 0.40$) (Table 4).

Adults located during snorkeling surveys were distributed as follows with respect to habitat cell classification: optimal = 0, usable = 5, suitable = 20, unsuitable = 9 (Figures 9-11). These results indicate significant selection for usable or suitable habitat over unsuitable ($\chi^2 = 24.5$, $\underline{P} < 0.0001$) (Table 4).

Habitat in Baron Fork was similar between 1999 and 2000. Each variable (depth, velocity, substrate, and cover) within each mesohabitat type (mid-channel pool, lateral pool, run, and riffle) was analyzed separately for each study site (Table 5). Eleven of forty-eight (22.9%) distributions were significantly different ($\underline{P} < 0.0125$) between years. By study sites, site 1 had the greatest amount of change in microhabitat distributions (31.3%), with five of sixteen distribution tests indicating significant change ($\underline{P} < 0.0125$). Mid-channel pools had the highest degree of change (41.7%), with five of twelve distribution tests showing significant change ($\underline{P}$ < 0.0125). When microhabitat variables were analyzed, depth and velocity accounted for 10 of the 11 significant differences (90.9%), while substrate accounted for the other significantly different microhabitat variable. Cover remained constant throughout the study and showed no significant change ($\underline{P}$ > 0.0125) for all mesohabitat types and study sites (Table 5).

All mesohabitat types exhibited high amounts of change in amount of cross-sectional area between 1999 and 2000. For example, the site 1 run transect at Eldon Bridge (Figure 12) had a 93.5% loss in cross-sectional area and a 93.5% absolute change in cross-sectional area. All depth measurements at transect points for 2000 were less than those in 1999 for this transect. The site 2 riffle transect at Baron Fork Ranch (Figure 13) had an 11.8% loss in cross-sectional area and a 62.5% absolute change in cross-sectional area. This channel had shifted approximately 20 m longitudinally. The site 3 mid-channel pool transect at Christie Bridge (Figure 14) had only a 6.3% loss in cross-sectional area but a 37.2% absolute change in cross-sectional area. The right bank of this transect was located on a rock bluff that prevented significant channel change. The site 2 lateral pool transect at Baron Fork Ranch (Figure 15) had an 84.8% loss in cross-sectional area and an 85% absolute change in cross-sectional area. This pool was also located adjacent to a rock bluff, but significant aggradation of channel-bed material occurred on the left bank of the transect which decreased width of the stream channel.

Flood events that occurred between sampling periods had altered the position of the channel and its overall shape. Visual examination of the channel revealed substantial lateral channel movement in sites 1(Figure 16) and 3 (Figure 17) but minimal change in site 2 (Figures 18).

There was high variability in observed and predicted WUA for both adults and juveniles, but observed WUA was generally lower. Different discharges observed between study sites in 2000 precluded statistical testing for significance. Observed WUA per 1000 m of stream compared with predicted WUA for adults were: 197 m^2 versus 695 m^2 for site 1, 242 m^2 versus 587 m^2 for site 2, 438 m^2 versus 1328 m^2 for site 3. Observed WUA per 1000 m of stream compared with predicted WUA for juveniles were: 153 m^2 versus 3255 m^2 for site 1, 110 m^2 versus 1635 m^2 for site 2, 276 m^2 versus 4164 m^2 for site 3 (Table 6).

Discussion

Our goal was to use PHABSIM to evaluate hydraulic and habitat model predictions of available smallmouth bass habitat in an alluvial stream. Although alluvial streams by definition have unstable substrates, they are assumed to be in a state of dynamic equilibrium, where pools, runs, and riffles, and the channel may migrate from year to year but the mesohabitats remain in the same proportions (Richards 1982). An advantage of modeling habitat in alluvial streams is that these streams generally have gentle and very predictable slopes that result in effective hydraulic models over a wide range of discharges. Although these streams are assumed to be in a state of dynamic equilibrium, there is a lack of verification for the assumption of habitat stability in PHABSIM modeling, especially in warmwater streams where physical and hydrologic conditions are less predictable than in coldwater streams of western United States where PHABSIM originated (Mathur et al. 1985). Bedrock or boulder dominated streams, in contrast, pose a different problem for instream modeling. Habitat and hydraulic features can be measured over several seasons or years in these types of streams because they tend to be significantly more stable over time (Orth and Maughan 1982). However, it is much more difficult to model microhabitat in these stream because of their hydraulic complexity (Kondolf et al. 2000).

The goal of any habitat model is to simplify or reduce the number of variables to include only those of significance to the species of concern (Bovee 1986). By comparing predicted values of depth, velocity, and WUA with observed values it is possible to validate the model and identify possible errors in model predictions (Kondolf, et al. 2000). Validation involves measuring depth, velocity, substrate, and cover at random points in the study reach and comparing these with predicted values (Kondolf, et al. 2000). Our assessment of among-year transferability of HSC for adult and juvenile smallmouth bass identified limitations in juvenile HSC. We found a lack of significant use of suitable habitat cells by juvenile smallmouth bass over those classified as unsuitable. Additionally, our comparisons of predicted and observed WUA for juvenile smallmouth bass between 1999 and 2000 were highly variable. Juveniles often were found in shallower water than adults were and near the stream margin (Figures 6-11). Hydraulic models are imprecise near the stream margin (Kondolf et al. 2000), which may explain why model predictions differed from observations. In contrast, adult HSC were more consistent between years, possibly because adult fish occurred often in deeper pools. Another factor that may have affected the relative effectiveness in development of our models for juveniles and adults was the lower sample size for the former (N = 36 versus 64).

Habitat suitability criteria have been developed for smallmouth bass in other streams in Oklahoma (Edwards et al. 1983) as well as other states including Virginia (Leonard et al. 1986, Groshens and Orth 1994), Massachusetts (Bain et al. 1982), Michigan (Monahan 1991), Arizona (Barrett and Maughan 1994), and West Virginia (Newcomb et al. 1995). Differences between results from these studies and those we obtained for Baron Fork tended to be greater for juveniles than for adults. Our optimal and suitable ranges were generally higher than those reported in other studies. Optimal velocity HSC for adults in Baron Fork were within the range found in other studies as were suitable ranges compared to other studies (Appendix C). Similar results were found when comparing depth HSC for smallmouth bass with other studies. Optimal juvenile smallmouth bass HSC for depth were generally higher than those found in similar studies, whereas suitable ranges were more similar to other studies. Adult smallmouth bass depth HSC for the optimal category in Baron Fork were similar to those in similar studies. Suitable ranges for adult depth HSC were similar as well (Appendix D).

Maximum WUA occurred at similar stream discharges for juvenile (2.13 m^3/s) and adult (1.78 m^3/s) smallmouth bass, but the maximum for juveniles was more than three times greater than for adults. In an IFIM study of smallmouth bass in Glover River, Oklahoma, Orth and Maughan (1982) recommended discharges of 0.60 m^3/s for juveniles and 0.80 m^3/s for adults based on maximum WUA. These results differ from our estimates, possibly because of differences in hydrologic regime, geomorphology, and demographic differences between the two populations (Balkenbush and Fisher 1999). Baron Fork is an alluvial gravel-dominated spring-fed stream whereas Glover River is a bedrock-dominated runoff stream (Balkenbush and Fisher 1999).

Overall, similarities and dissimilarities between HSC and WUA found in this study emphasize the need for precisely measured fish-habitat data. Close correspondence between adult smallmouth bass locations in 2000 and HSC developed in 1999 suggest that adult HSC were reliable. Furthermore, WUA observations in 2000 for adult smallmouth bass were similar (although somewhat higher) to those predicted with PHABSIM based on 1999 data. These analyses indicate PHABSIM modeling and HSC development are reliable for adult smallmouth bass in Baron Fork. The apparent inaccuracy of our PHABSIM modeling for juvenile smallmouth bass may reflect shortcomings in either the ability of PHABSIM to model stream-margin habitat or in our ability to accurately describe juvenile fish-habitat associations, or both.

There is a lack of linkage between PHABSIM and GIS, which limits display of spatial habitat use by warmwater stream fishes to changes in discharge. Correia et al. (1998) integrated GIS with HEC-2 hydraulic model, a component of PHABSIM, for comprehensive floodplain management. The problem with describing WUA on a GIS map is that the surface is two-dimensional. This makes it difficult to express habitat availability at different discharges without creating different themes for each discharge. We were able to apply PHABSIM cell values to GIS maps manually and use GIS to test transferability of HSC data for smallmouth bass. Along with these analyses, we were able to map our study sites accurately and visualize a change in channel location from 1999 to 2000. Seamless linkage of PHABSIM output with GIS would require little or no manual entry of data. GIS is capable of quantifying habitats based on size, shape, and connectivity of mesohabitats while modeling habitat suitability based on depth, velocity, substrate, cover, and any other factors found to affect fish distributions. These functions enabled us to predict similar values of WUA for sampled sites based on measurements taken at the time of the study with GIS. PHysical HABitat SIMulation is needed to predict unmeasured discharges. Hydraulic programs such as WSP, MANSQ, and STGQ allow PHABSIM to accurately model unmeasured depths and velocities of habitat cells. If these programs could be integrated into GIS, then habitat could be modeled effectively in a multi-dimensional analysis. Nevertheless, GIS was a valuable tool for identifying critical habitats and their change over time in our study.

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Table 1. The 25th percentile, 50th percentile (median), and 75th percentile monthly discharge values (m^3/s) for the Baron Fork of the Illinois River station at Eldon Bridge (number 07197000) from 1948 -1999 during low-flow months of August - October.

Month	25th percentile	Median	75th Percentile
August	0.68	1.25	2.12
September	0.54	1.01	2.01
October	0.65	1.41	2.80

Table 2. Number, area, and distance of mesohabitat types identified in a 21.5 km segment of Baron Fork.

Mesohabitat type	Number	Percent number	Total Area (m^2)	Percent area	Distance (m)
Backwater pool	27	10.8%	16,405	3.7%	1,161
Mid-channel pool	37	14.9%	102,405	23.0%	4,940
Lateral pool	40	16.1%	73,628	16.6%	3,632
Run	82	32.9%	163,221	36.8%	8,553
Riffle	63	25.3%	88,534	19.9%	5,059
Total	249	100.0%	444,193	100.0%	23,345

Table 3. Habitat suitability criteria for juvenile and adult smallmouth bass in Baron Fork, Oklahoma. See Appendix A for an explanation of substrate and cover codes.

Habitat quality	Habitat variable	
	Juvenile	Adult
Depth (cm)		
Optimal	35-115	55-155
Usable	15-135	25-180
Suitable	5-150	5-200
Velocity (cm/s)		
Optimal	25-80	10-30
Usable	10-95	5-35
Suitable	0-105	0-40
Substrate (code)		
Optimal	7	8
Usable	7,8	6,8,11
Suitable	4,6-9	4,6-12
Cover (code)		
Optimal	1	4
Usable	1,4,5	1,4,6
Suitable	0,1,3-6	0,1,3,4,6

Table 4. Juvenile and adult smallmouth bass occupied versus unoccupied cells based on snorkeling observations (2000) and HSC developed from electrofishing data (1999) with chi-square values and associated P-values. For juveniles; optimal, usable, and suitable categories were combined. For adults; optimal and usable categories were combined. Significant at P < 0.05 (*).

	Suitability	**Presence**	**N**
Juveniles	Optimal	Unoccupied	0
$\chi^2 = 0.71$	Usable	Unoccupied	3
P = 0.40	Suitable	Unoccupied	197
	Unsuitable	Unoccupied	135
	Optimal	Occupied	0
	Usable	Occupied	0
	Suitable	Occupied	26
	Unsuitable	Occupied	13
Adults	Optimal	Unoccupied	1
$\chi^2 = 24.50$	Usable	Unoccupied	3
P < 0.0001*	Suitable	Unoccupied	211
	Unsuitable	Unoccupied	125
	Optimal	Occupied	0
	Usable	Occupied	5
	Suitable	Occupied	20
	Unsuitable	Occupied	9

Table 5. Maximum values of deviation (Δ) for determination of Kolmogorov-Smirnov statistic. Significant amount of change ($\underline{P}<0.05$) in habitat availability at sites 1,2,3 for mid-channel pools, lateral pools, runs, and riffles denoted by asterisk (*). Bonferroni correction was used within each variable and site, example for depth in site 1, $\alpha/4 = 0.0125$.

Mesohabitat Type	Δ Depth (m)	Δ Velocity (m/s)	Δ Substrate (code)	Δ Cover (code)
		Site 1 N=51		
Mid-Channel Pool	1.27*	0.04*	7*	1
Lateral Pool	0.65*	0.21*	9	4
Run	0.42	0.36	7	0
Riffle	0.26	0.11	7	0
		Site 2 N=74		
Mid-Channel Pool	1.07	0.09*	7	0
Lateral Pool	0.52	0.06	7	0
Run	0.31*	0.33	7	0
Riffle	0.16	0.53	7	4
		Site 3 N=79		
Mid-Channel Pool	0.33*	0.08	8	0
Lateral Pool	-	-	-	-
Run	0.48	0.06*	4	0
Riffle	0.23*	0.72*	7	0

Table 6. Predicted (1999) and observed (2000) WUA (m^2) for juvenile and adult smallmouth bass. Each value is also displayed with total area (m^2) available and percent of total area accounted for by WUA. Discharges were as follows: site 1 = 1.13 m^3/s, site 2 = 0.57 m^3/s, site 3 = 1.42 m^3/s.

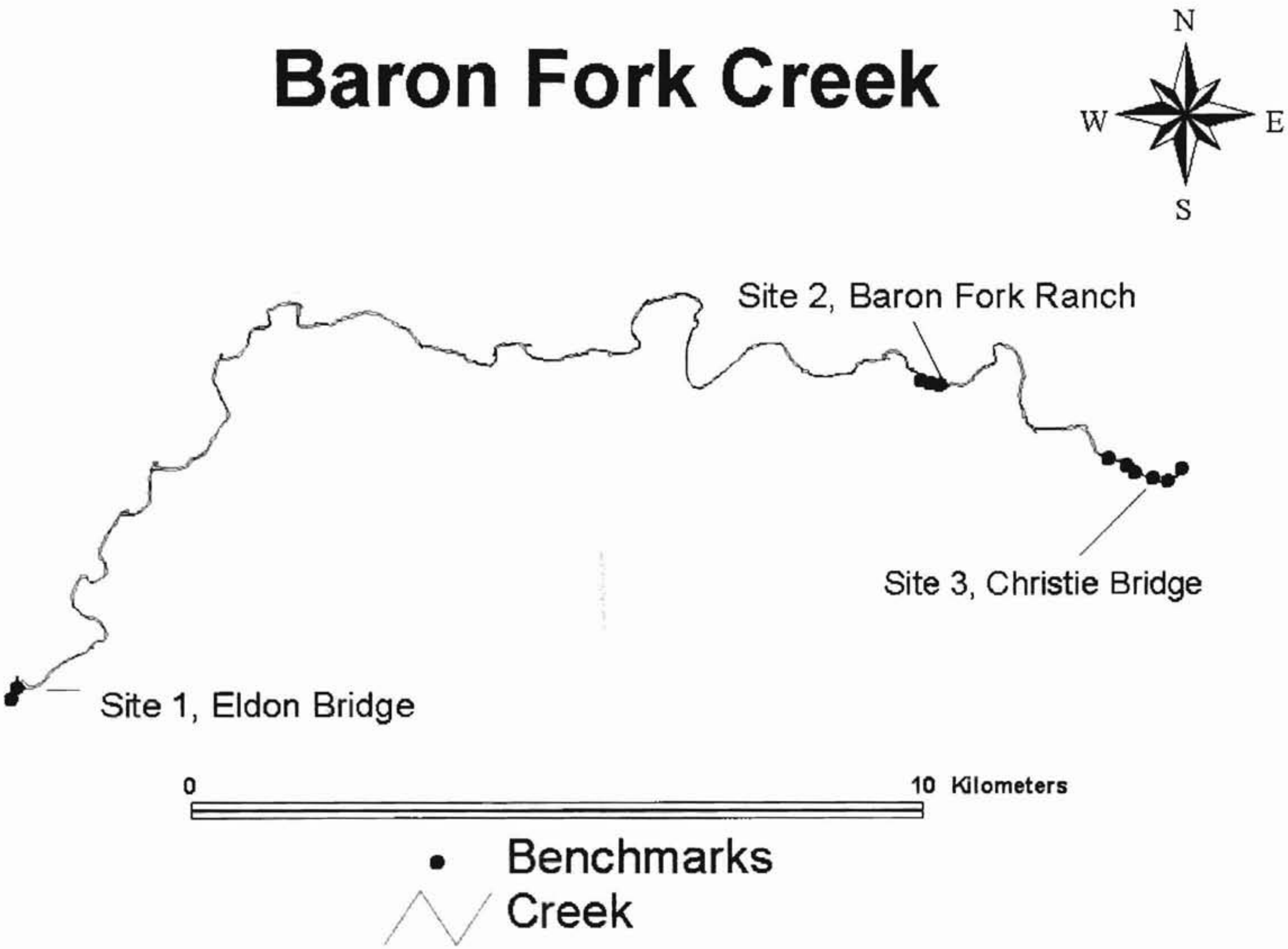
	WUA (m^2)	Total Area (m^2)	Percent (%)
		Juvenile	
Site 1			
Observed	153	25,285	0.6
Predicted	3255	23,825	13.7
Site 2			
Observed	110	23,756	0.5
Predicted	1635	15,118	10.8
Site 3			
Observed	276	20,752	1.3
Predicted	4164	20,844	20.0
		Adult	
Site 1			
Observed	197	25,285	0.8
Predicted	695	23,825	2.9
Site 2			
Observed	242	23,756	1.0
Predicted	587	15,118	3.9
Site 3			
Observed	438	20,752	2.1
Predicted	1301	20,844	6.2

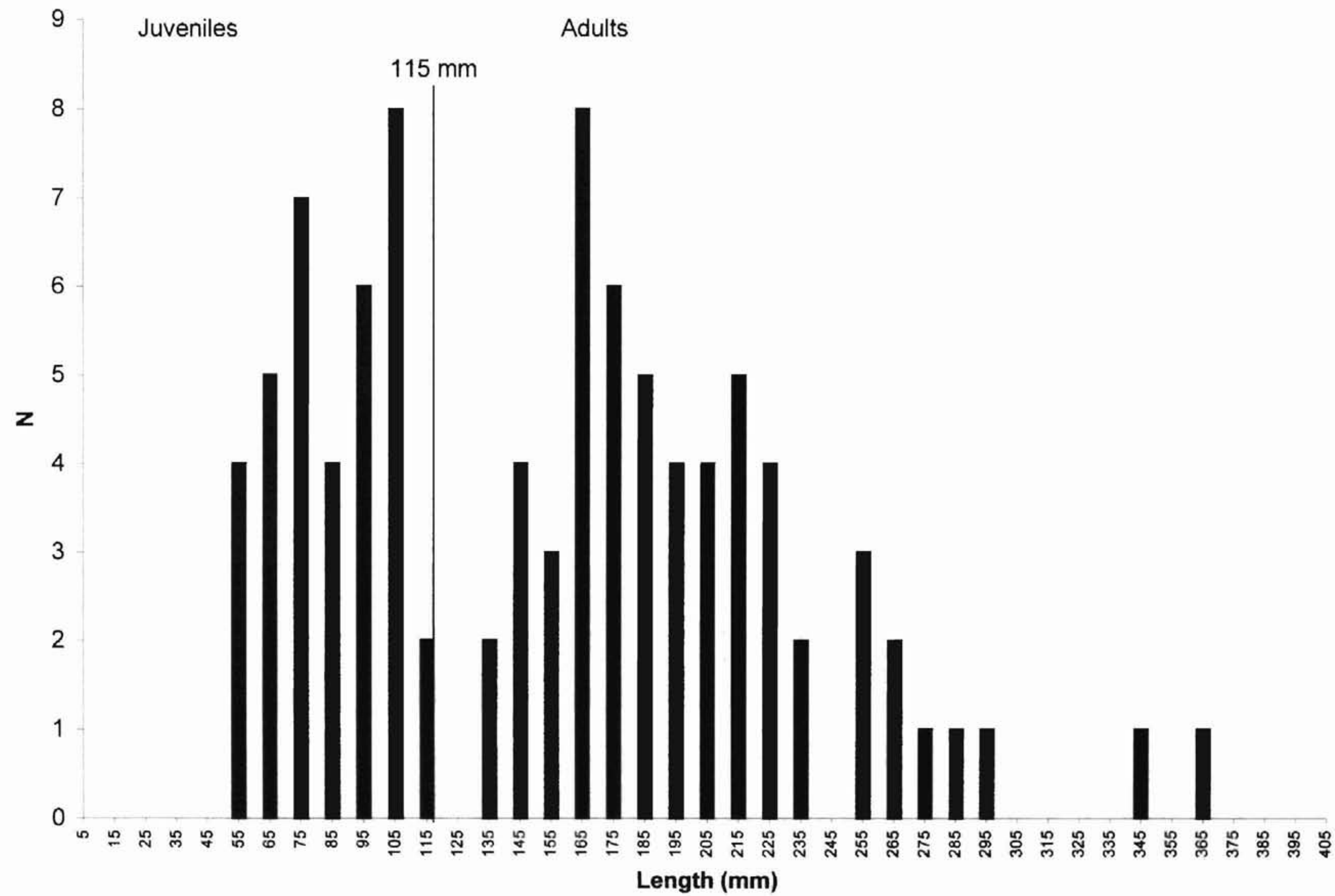
Figure Captions

1. Site map of study segment in Baron Fork of the Illinois River.
2. Length frequency distributions of smallmouth bass captured for development of habitat suitability criteria during 1999.
3. Monthly median discharge values (1948-1999) for the Baron Fork at Eldon gauge (station number 07197000).
4. Weighted Usable Area calculations for adult and juvenile smallmouth bass in Baron Fork of the Illinois River.
5. Adult and juvenile smallmouth bass time series analysis curves showing 25%, 50%, and 75% discharges with Weighted Usable Area for July through November.
6. Habitat suitability classes and locations of juvenile smallmouth bass for site 1 (Eldon Bridge).
7. Habitat suitability classes and locations of juvenile smallmouth bass for site 2 (Baron Fork Ranch).
8. Habitat suitability classes and locations of juvenile smallmouth bass for site 3 (Christie Bridge).
9. Habitat suitability classes and locations of adult smallmouth bass for site 1 (Eldon Bridge).
10. Habitat suitability classes and locations of adult smallmouth bass for site 2 (Baron Fork Ranch).

Figure Captions (cont.)

11. Habitat suitability classes and locations of adult smallmouth bass for site 3 (Christie Bridge).
12. Cross-section profiles of a transect through a run mesohabitat in 1999 and 2000.
13. Cross-section profiles of a transect through a riffle mesohabitat in 1999 and 2000.
14. Cross-section profiles of a transect through a mid-channel pool mesohabitat in 1999 and 2000.
15. Cross-section profiles of a transect through a lateral pool mesohabitat in 1999 and 2000.
16. Map for site 1 (Eldon Bridge) showing 1999 channel and 2000 channel with mesohabitat types.
17. Map for site 3 (Christie Bridge) showing 1999 channel and 2000 channel with mesohabitat types.
18. Map for site 2 (Baron Fork Ranch) showing 1999 channel and 2000 channel with mesohabitat types.


Baron Fork Creek
N
W
E
S
Site 2, Baron Fork Ranch
Site 3, Christie Bridge
Site 1, Eldon Bridge
0
10 Kilometers
Benchmarks
Creek



Juveniles
Adults
115 mm
N
Length (mm)
0
1
2
3
4
5
6
7
8
9
5
15
25
35
45
55
65
75
85
95
105
115
125
135
145
155
165
175
185
195
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365
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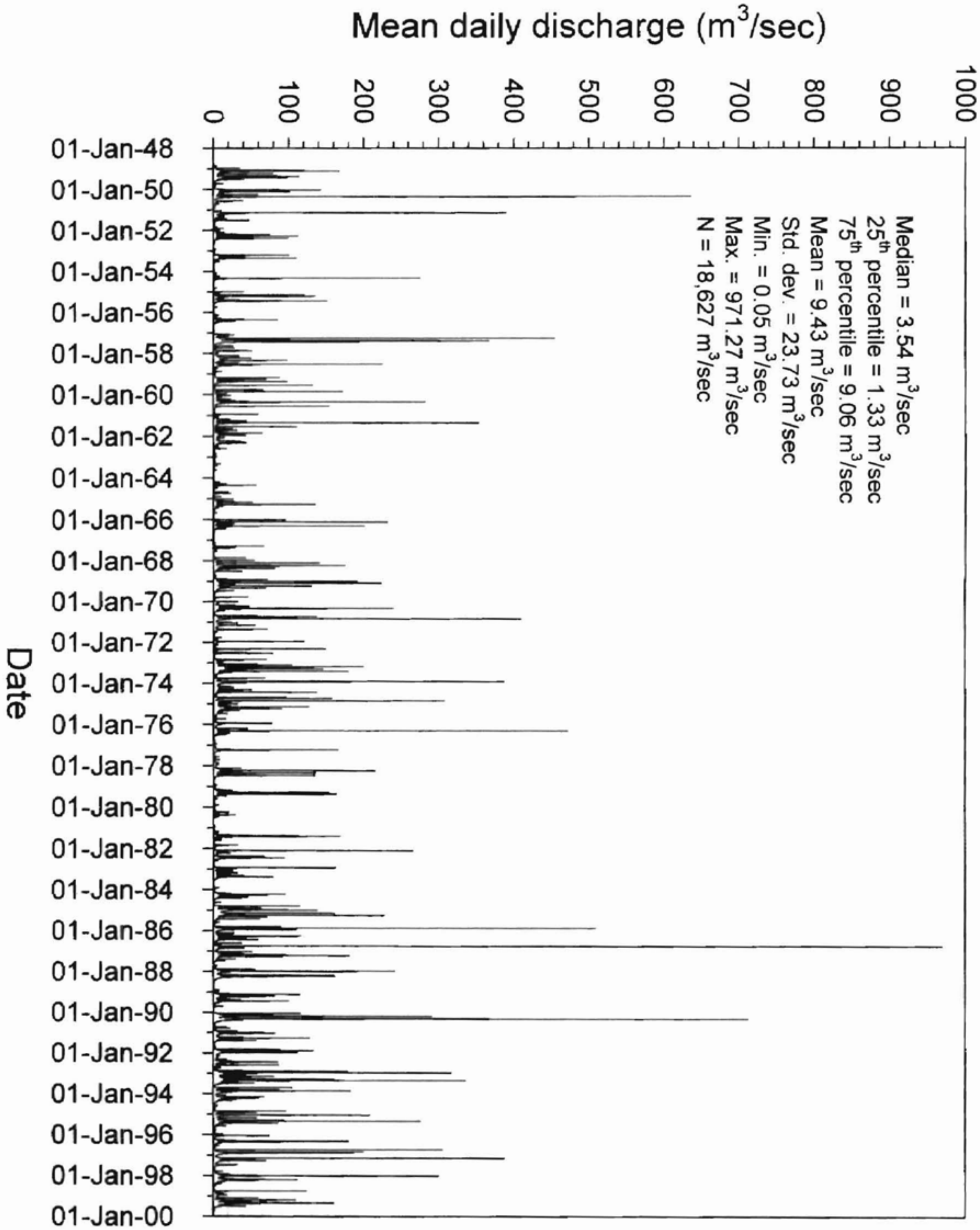
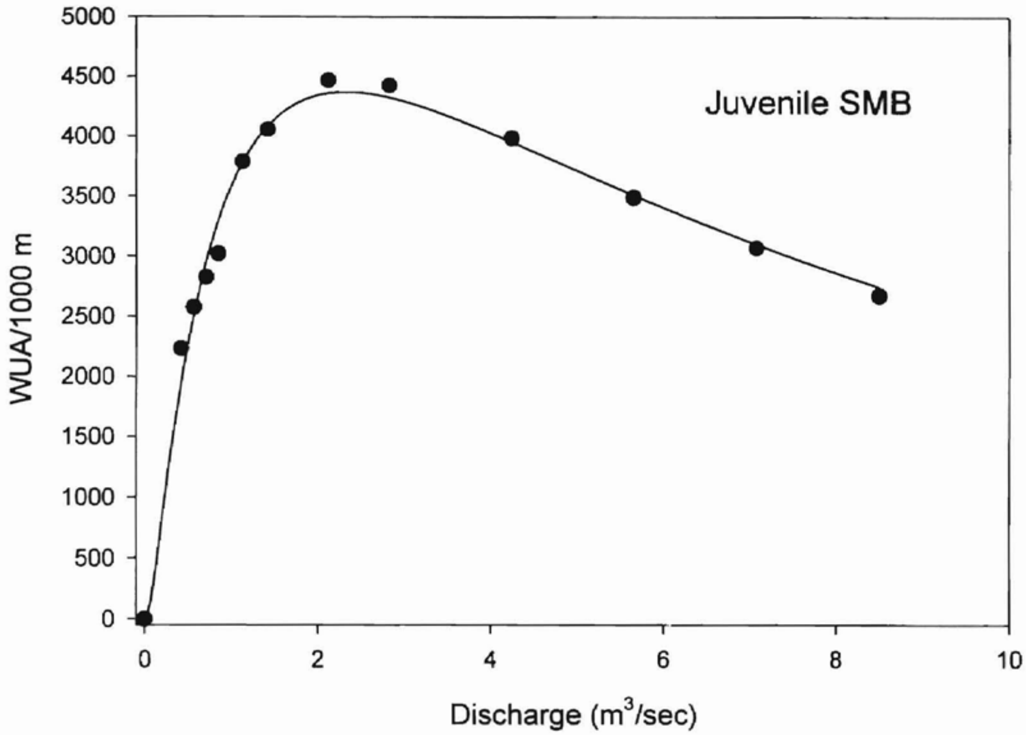
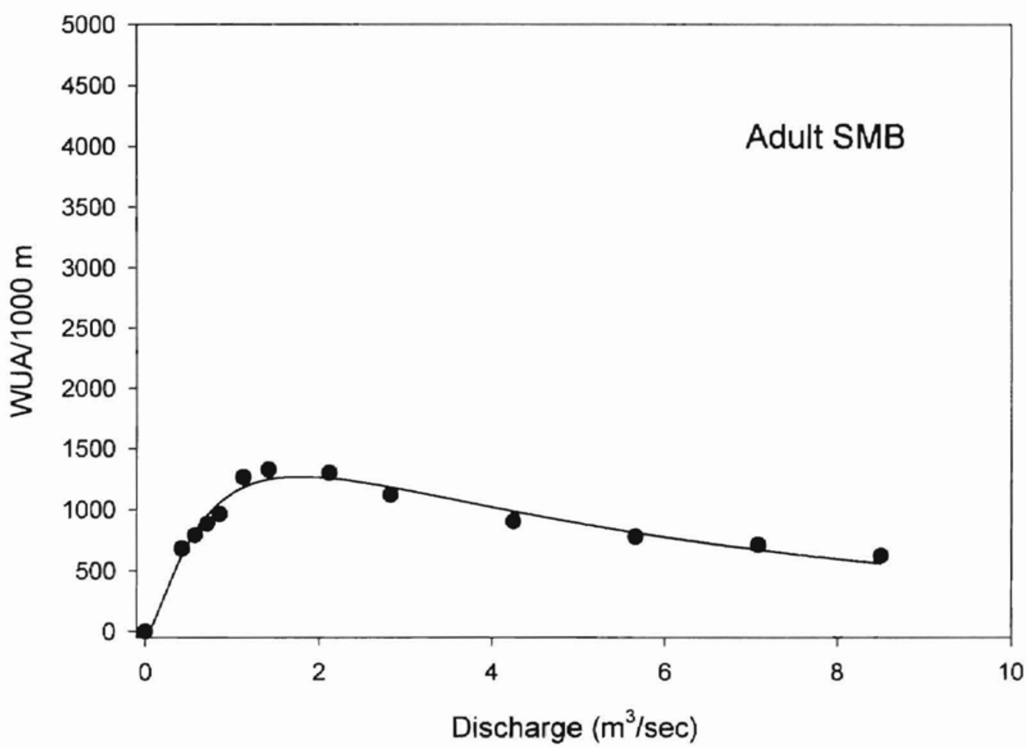
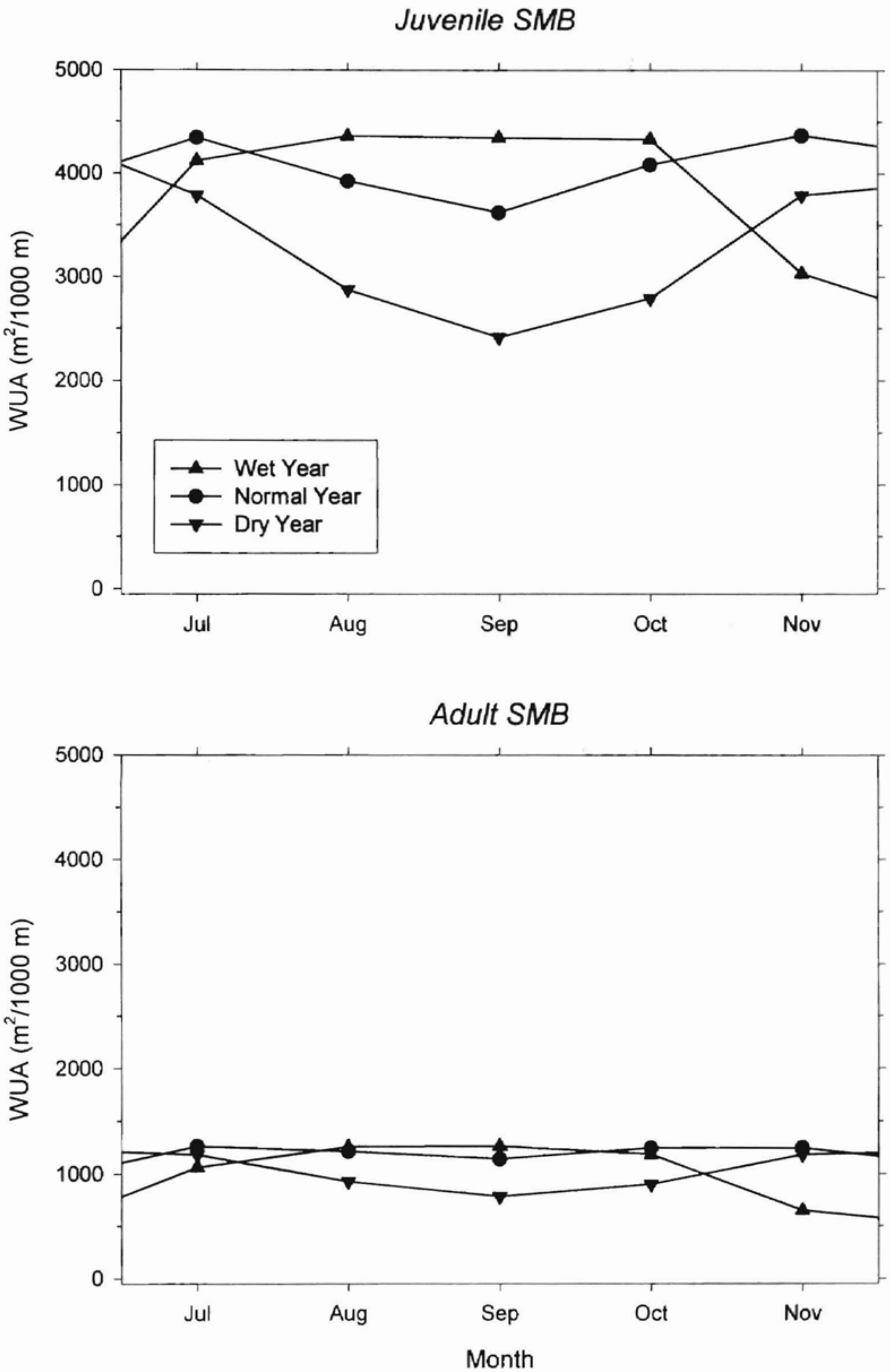
385
395
405



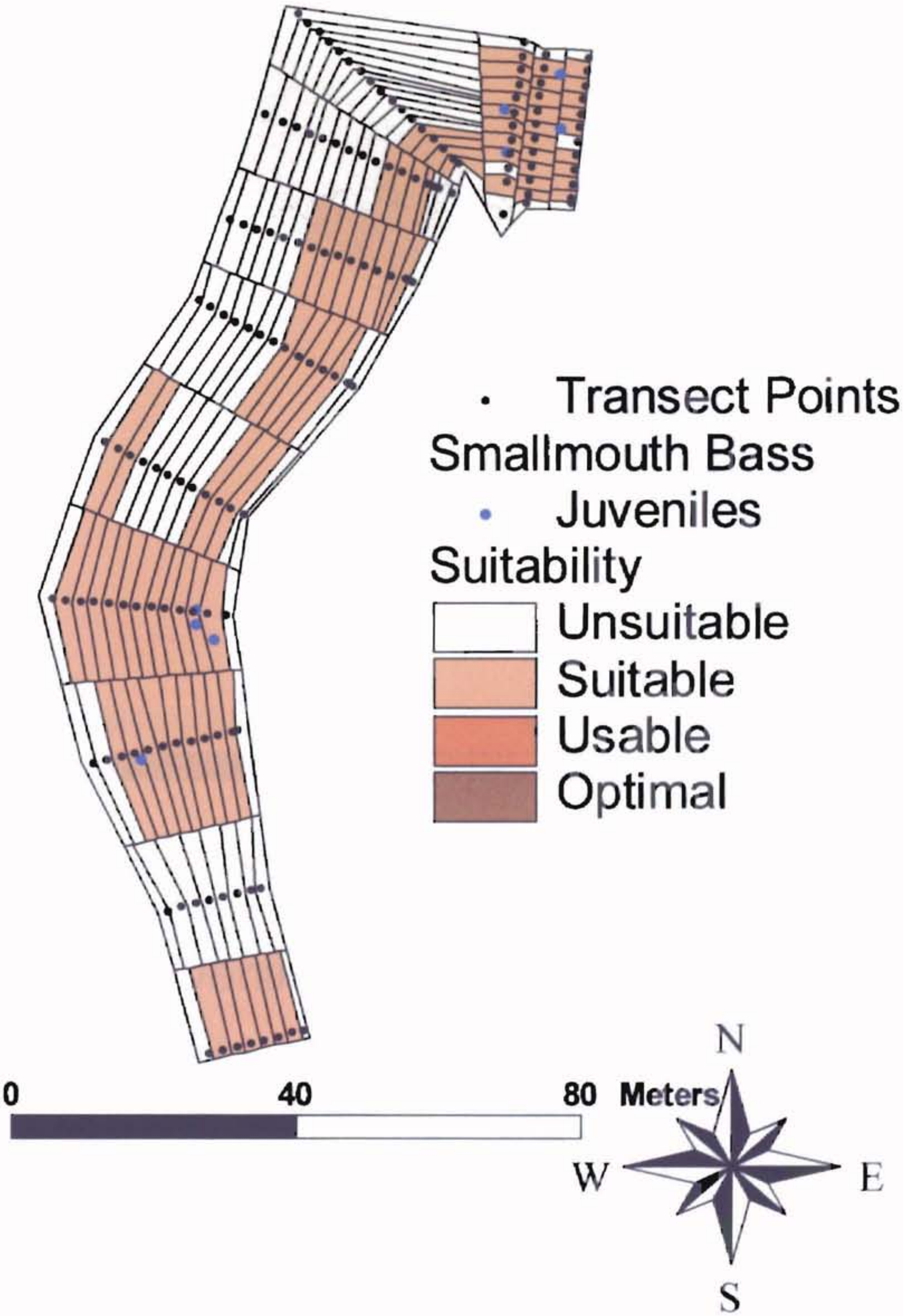
Mean daily discharge (m3/sec)
0
100
200
300
400
500
600
700
800
900
1000
Date
01-Jan-48
01-Jan-50
01-Jan-52
01-Jan-54
01-Jan-56
01-Jan-58
01-Jan-60
01-Jan-62
01-Jan-64
01-Jan-66
01-Jan-68
01-Jan-70
01-Jan-72
01-Jan-74
01-Jan-76
01-Jan-78
01-Jan-80
01-Jan-82
01-Jan-84
01-Jan-86
01-Jan-88
01-Jan-90
01-Jan-92
01-Jan-94
01-Jan-96
01-Jan-98
01-Jan-00
Median = 3.54 m3/sec
25th percentile = 1.33 m3/sec
75th percentile = 9.06 m3/sec
Mean = 9.43 m3/sec
Std. dev. = 23.73 m3/sec
Min. = 0.05 m3/sec
Max. = 971.27 m3/sec
N = 18,627 m3/sec


5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
WUA/1000 m
Juvenile SMB
0
2
4
6
8
10
Discharge (m3/sec)

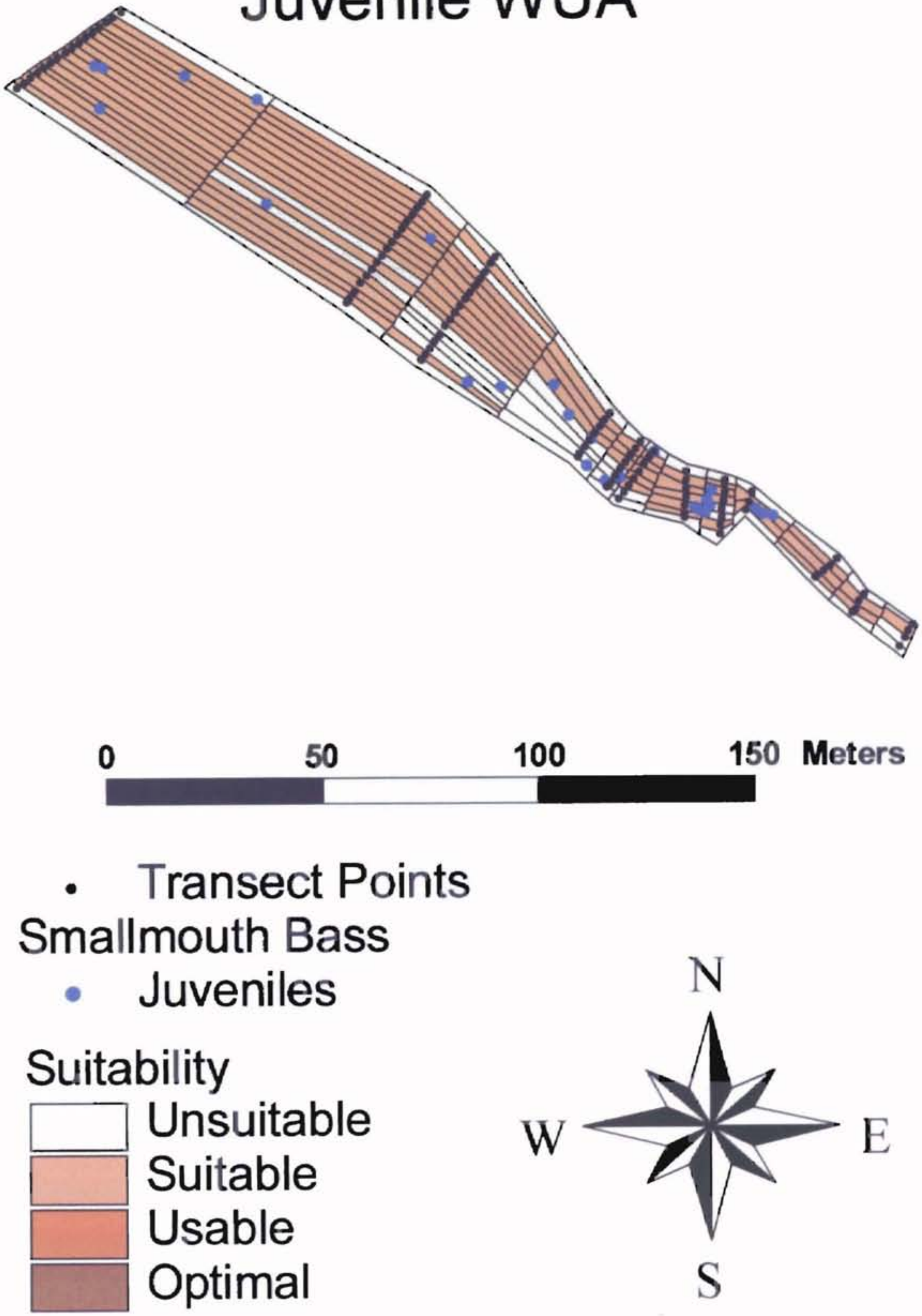

5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
WUA/1000 m
Adult SMB
0
2
4
6
8
10
Discharge (m3/sec)


Juvenile SMB
5000
4000
3000
2000
1000
0
WUA (m2/1000 m)
Wet Year
Normal Year
Dry Year
Jul
Aug
Sep
Oct
Nov
Adult SMB
5000
4000
3000
2000
1000
0
WUA (m2/1000 m)
Jul
Aug
Sep
Oct
Nov
Month

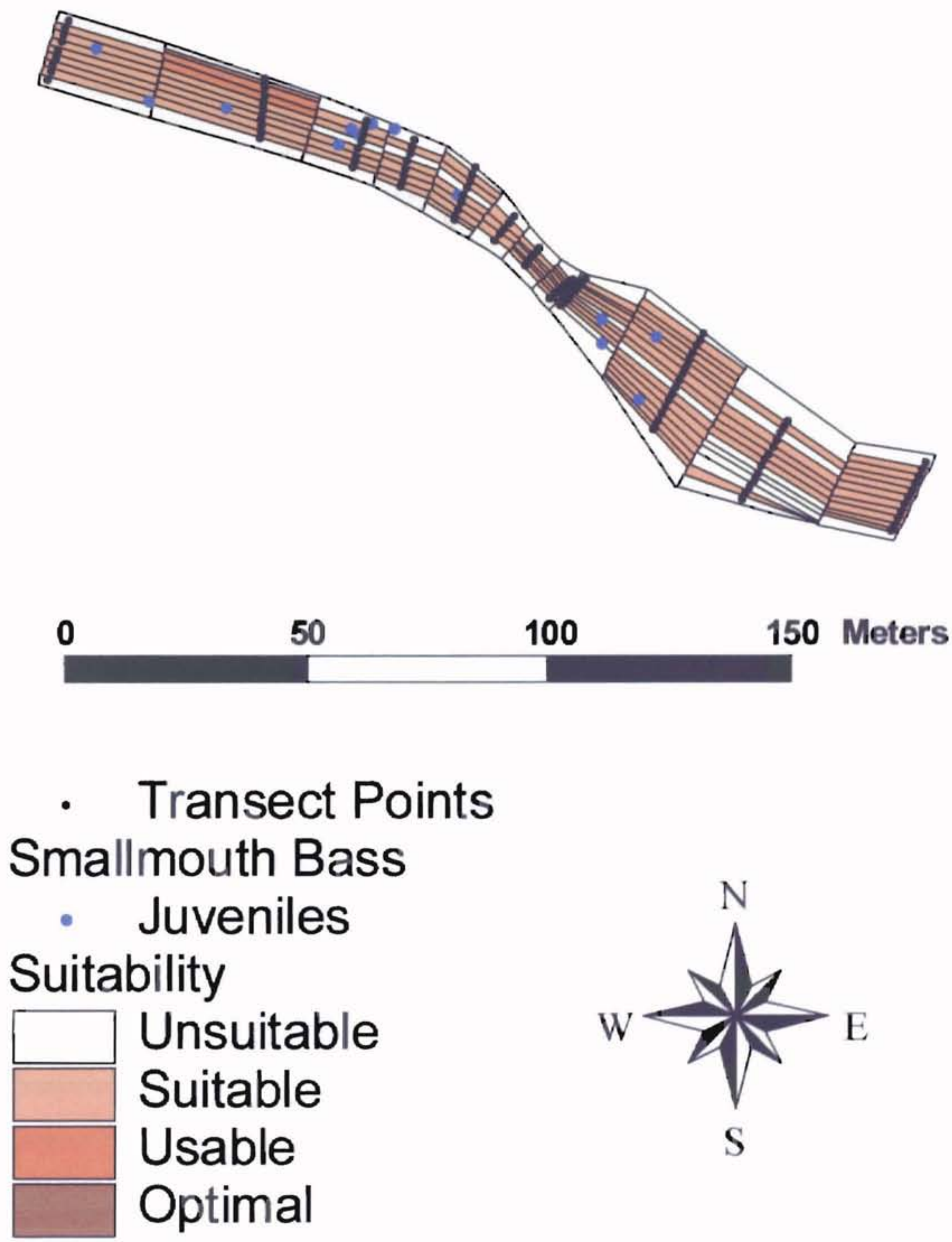
Site 1
Juvenile WUA



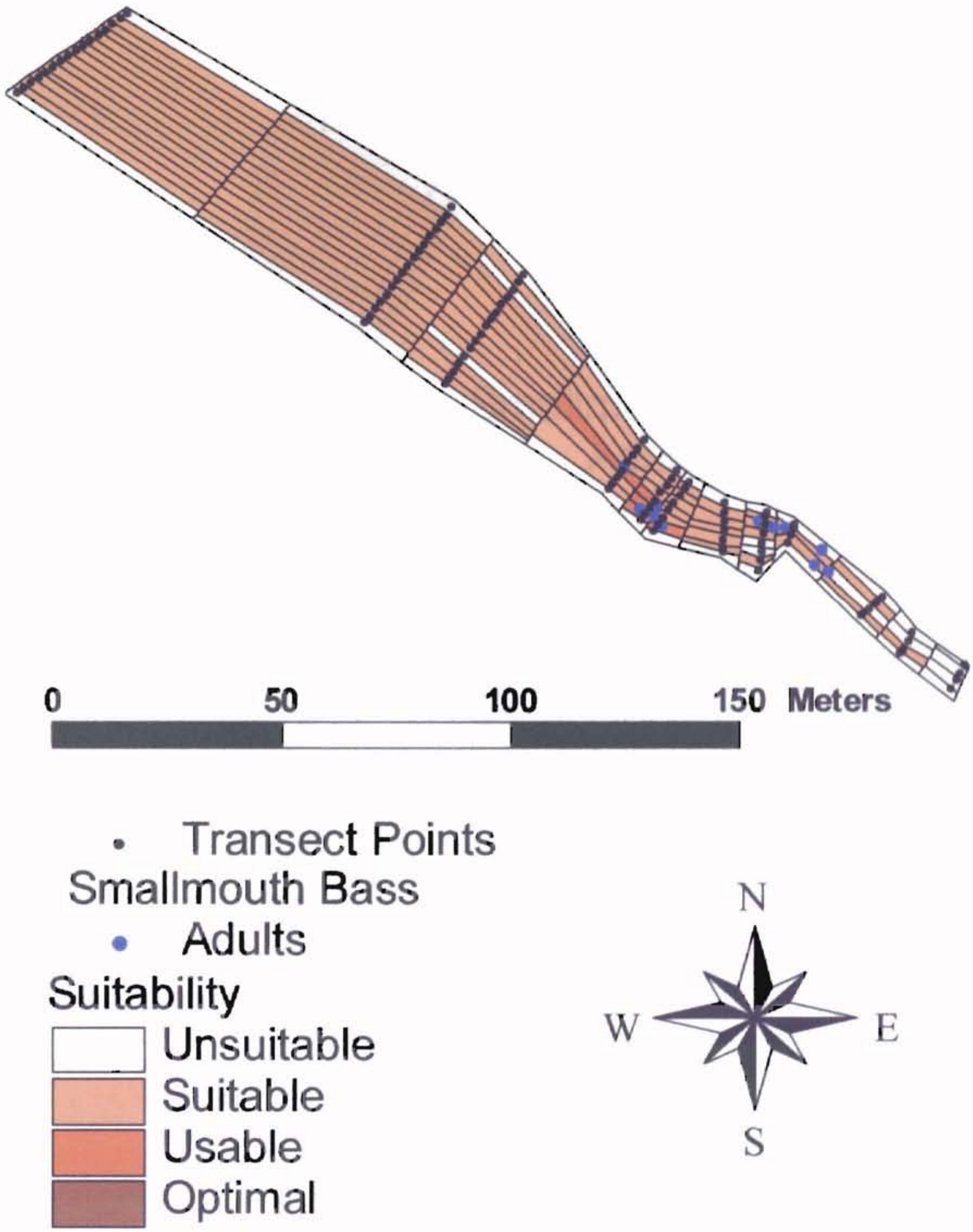
Site 2
Juvenile WUA



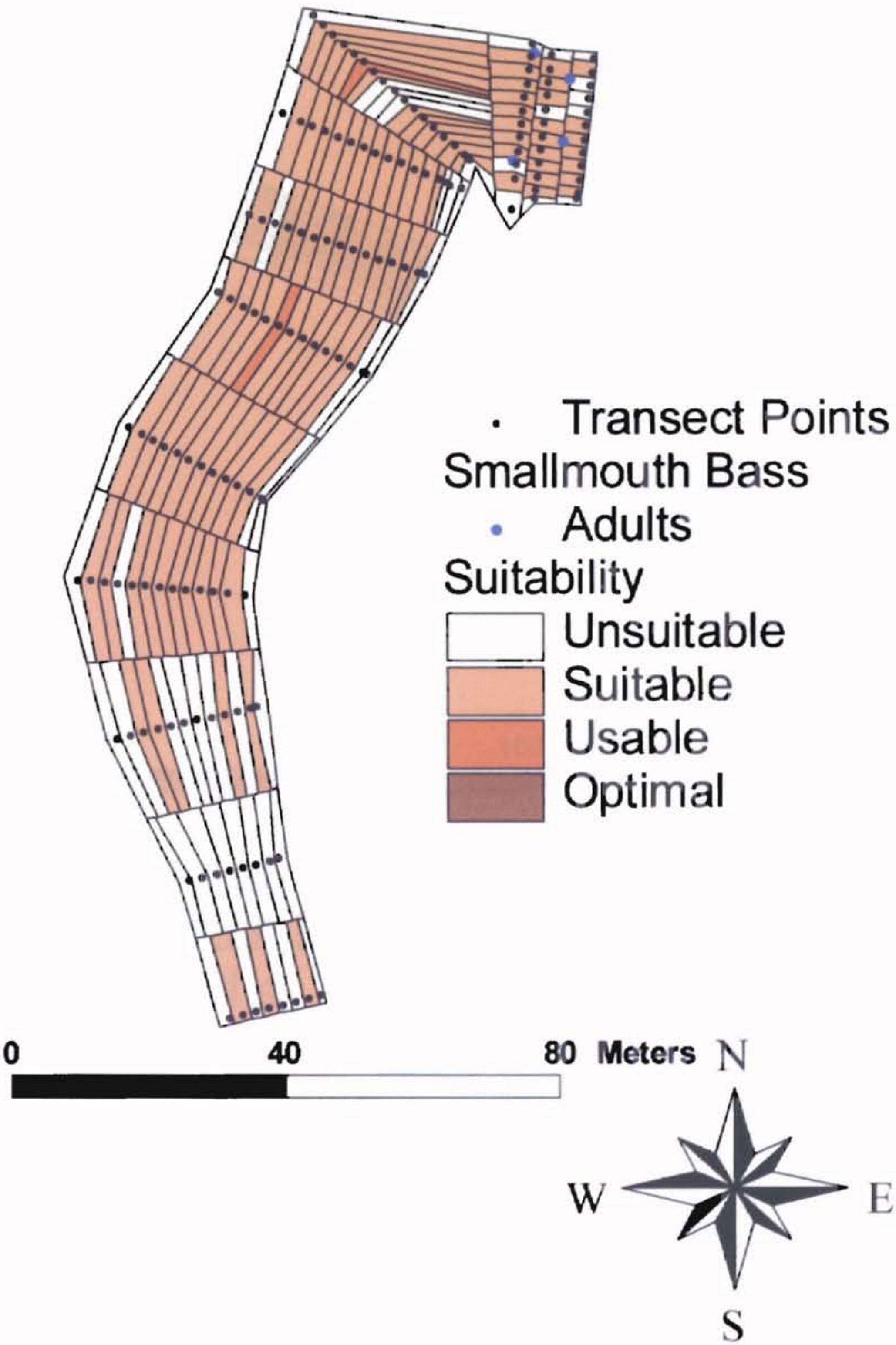
Site 3
Juvenile WUA



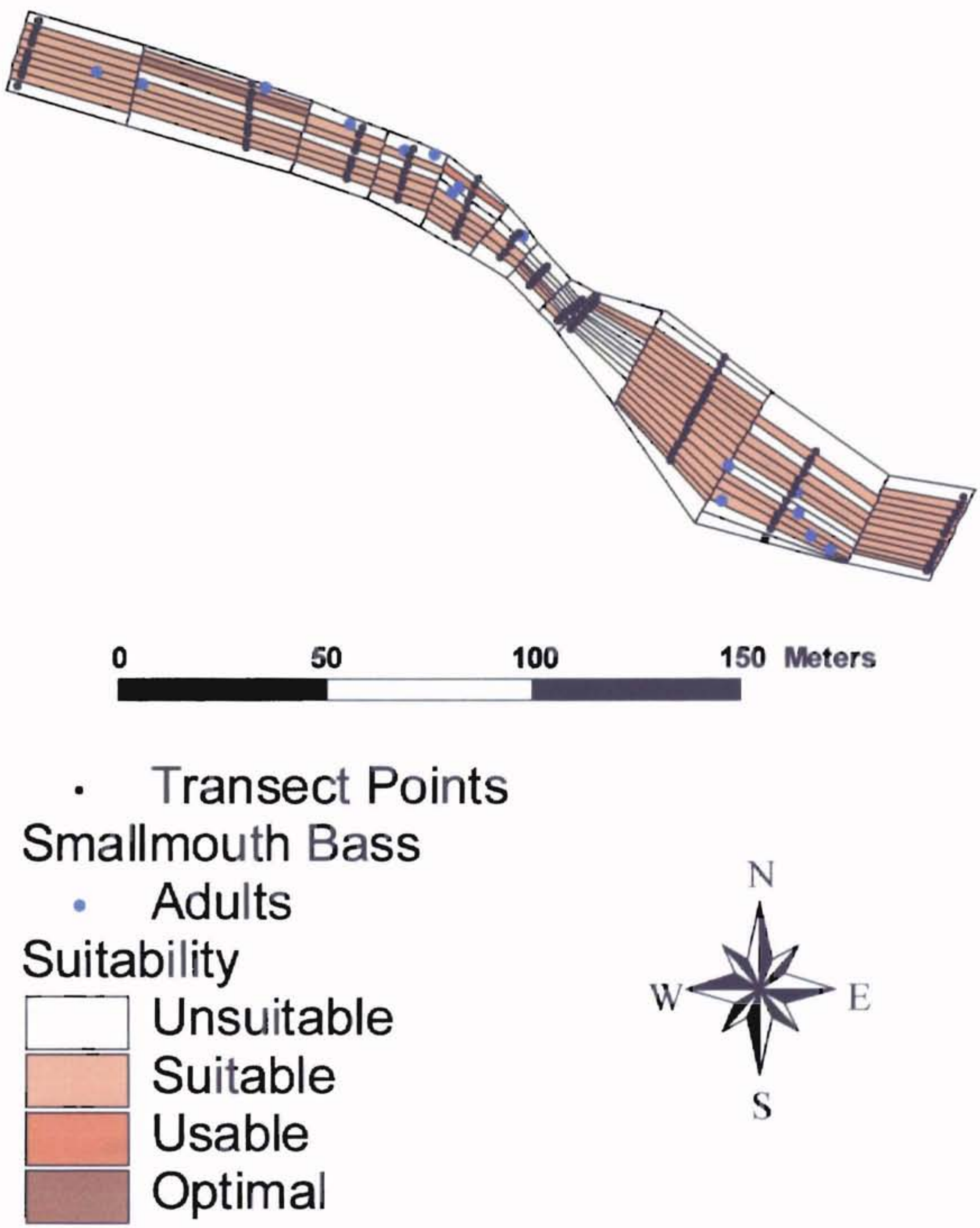
Site 2
Adult WUA

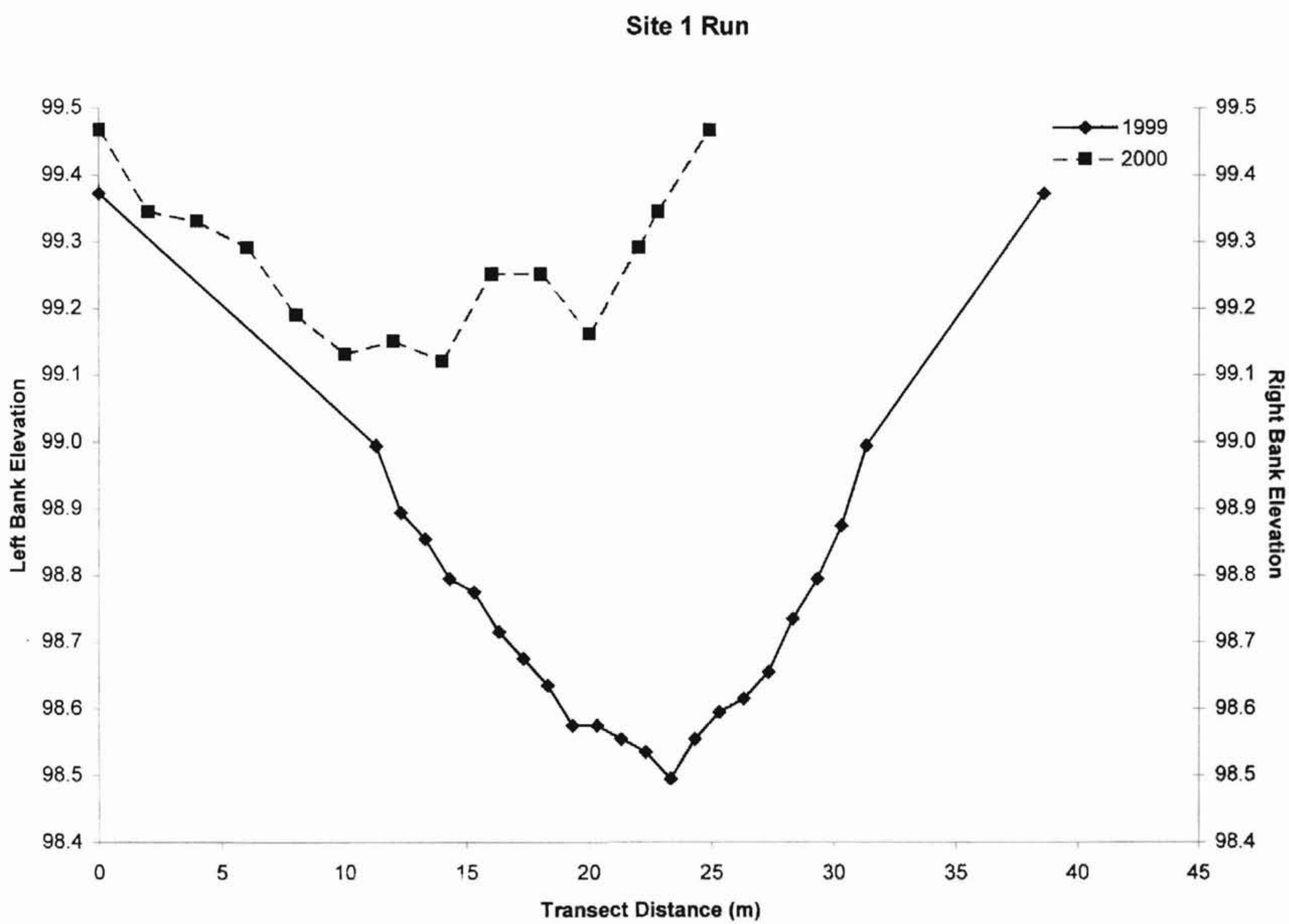


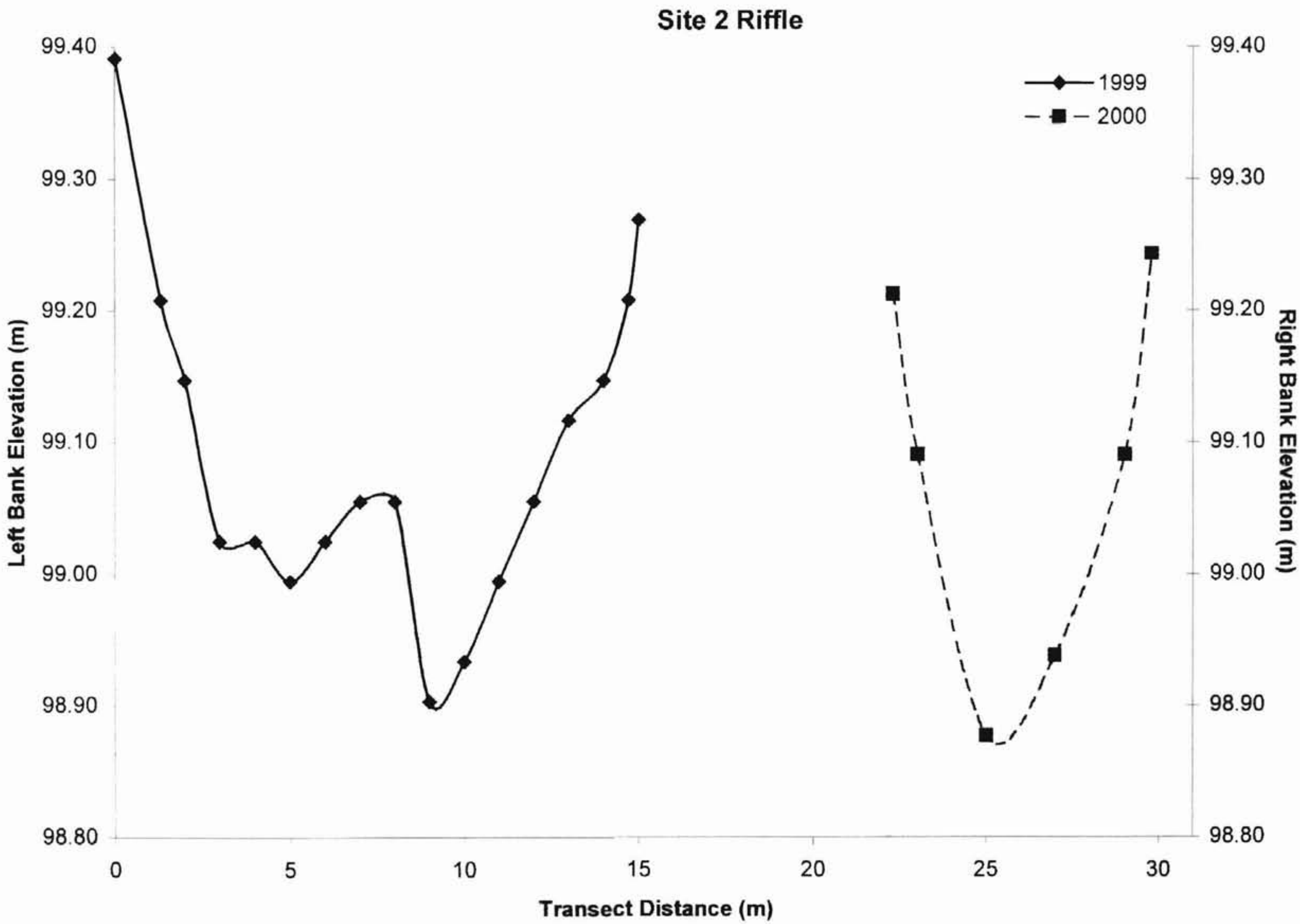
Site 1
Adult WUA

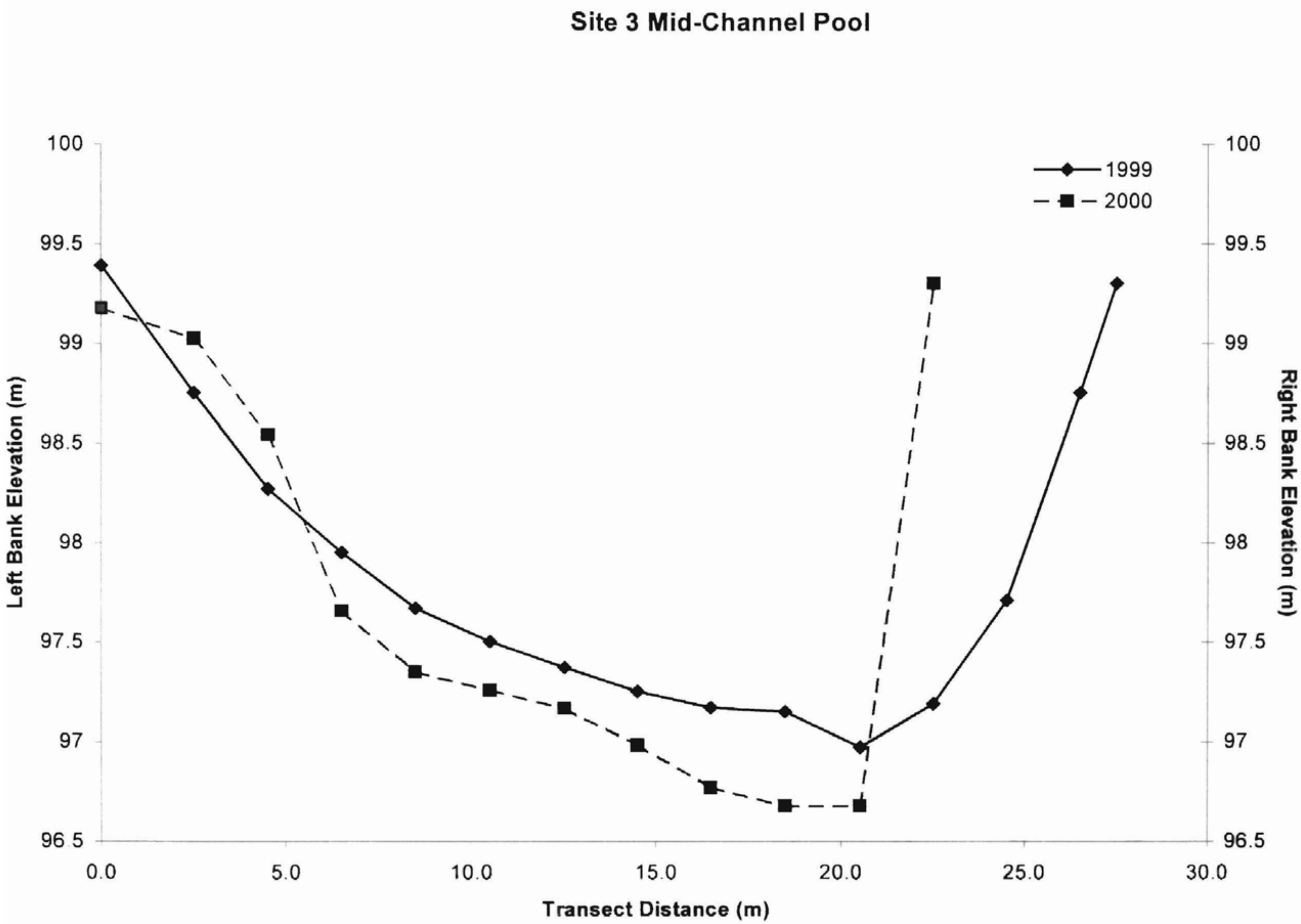


Site 3
Adult WUA

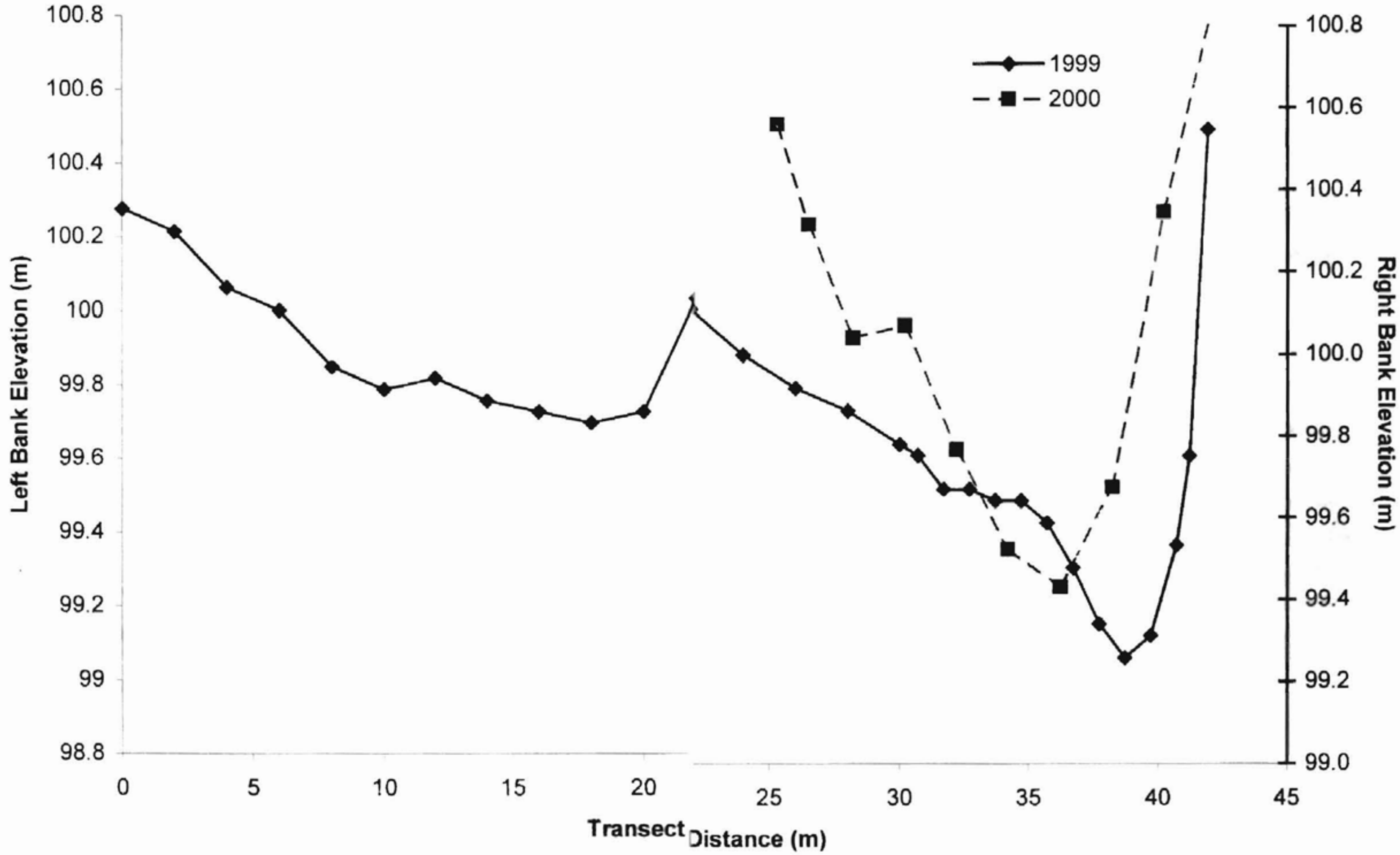



Site 1 Run
Left Bank Elevation
Right Bank Elevation
Transect Distance (m)
1999
2000
99.5
99.4
99.3
99.2
99.1
99.0
98.9
98.8
98.7
98.6
98.5
98.4
0
5
10
15
20
25
30
35
40
45

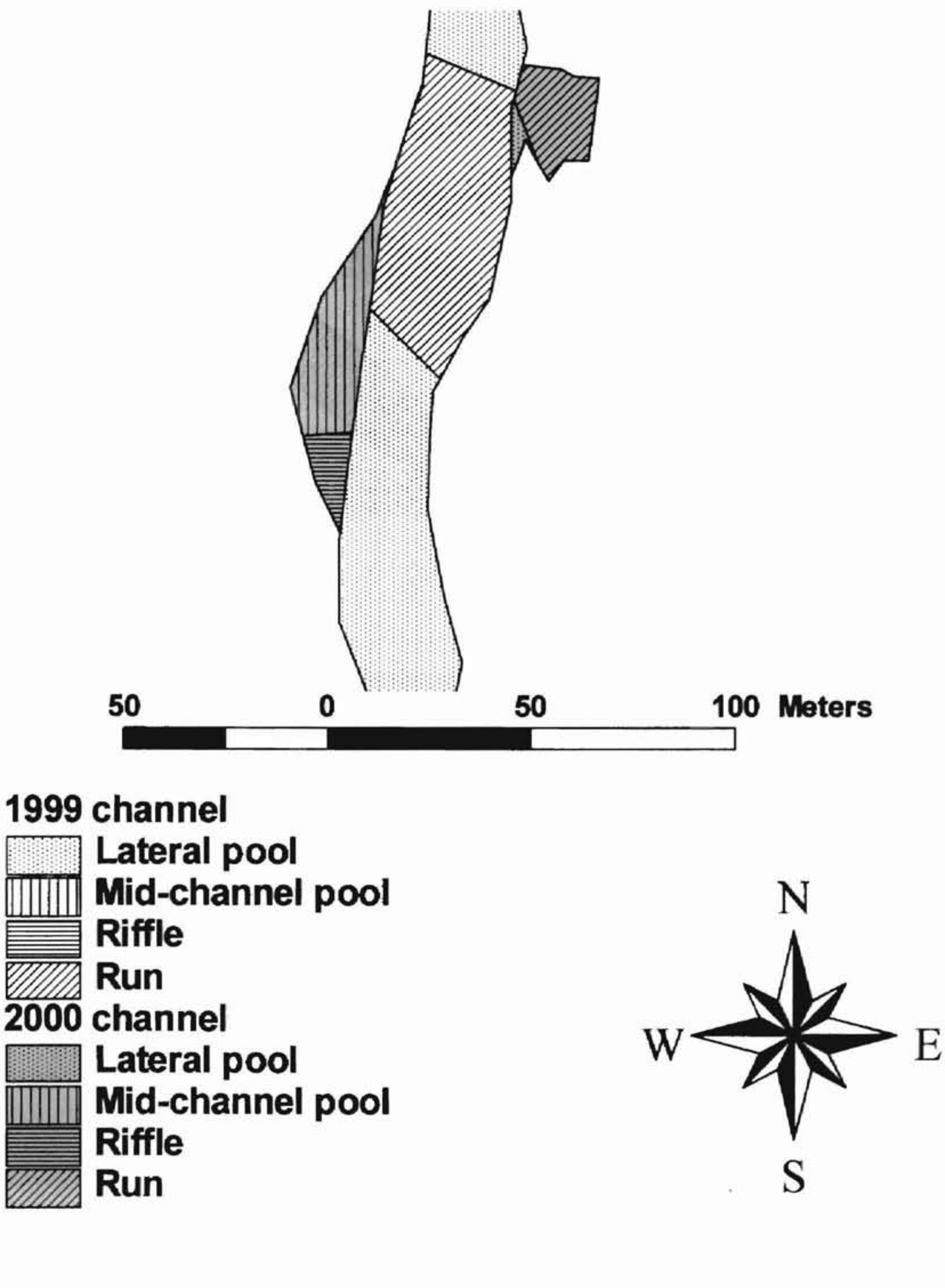

Site 2 Riffle
1999
2000
Left Bank Elevation (m)
Right Bank Elevation (m)
Transect Distance (m)
99.40
99.30
99.20
99.10
99.00
98.90
98.80
0
5
10
15
20
25
30


Site 3 Mid-Channel Pool
1999
2000
Left Bank Elevation (m)
Right Bank Elevation (m)
Transect Distance (m)
100
99.5
99
98.5
98
97.5
97
96.5
0.0
5.0
10.0
15.0
20.0
25.0
30.0

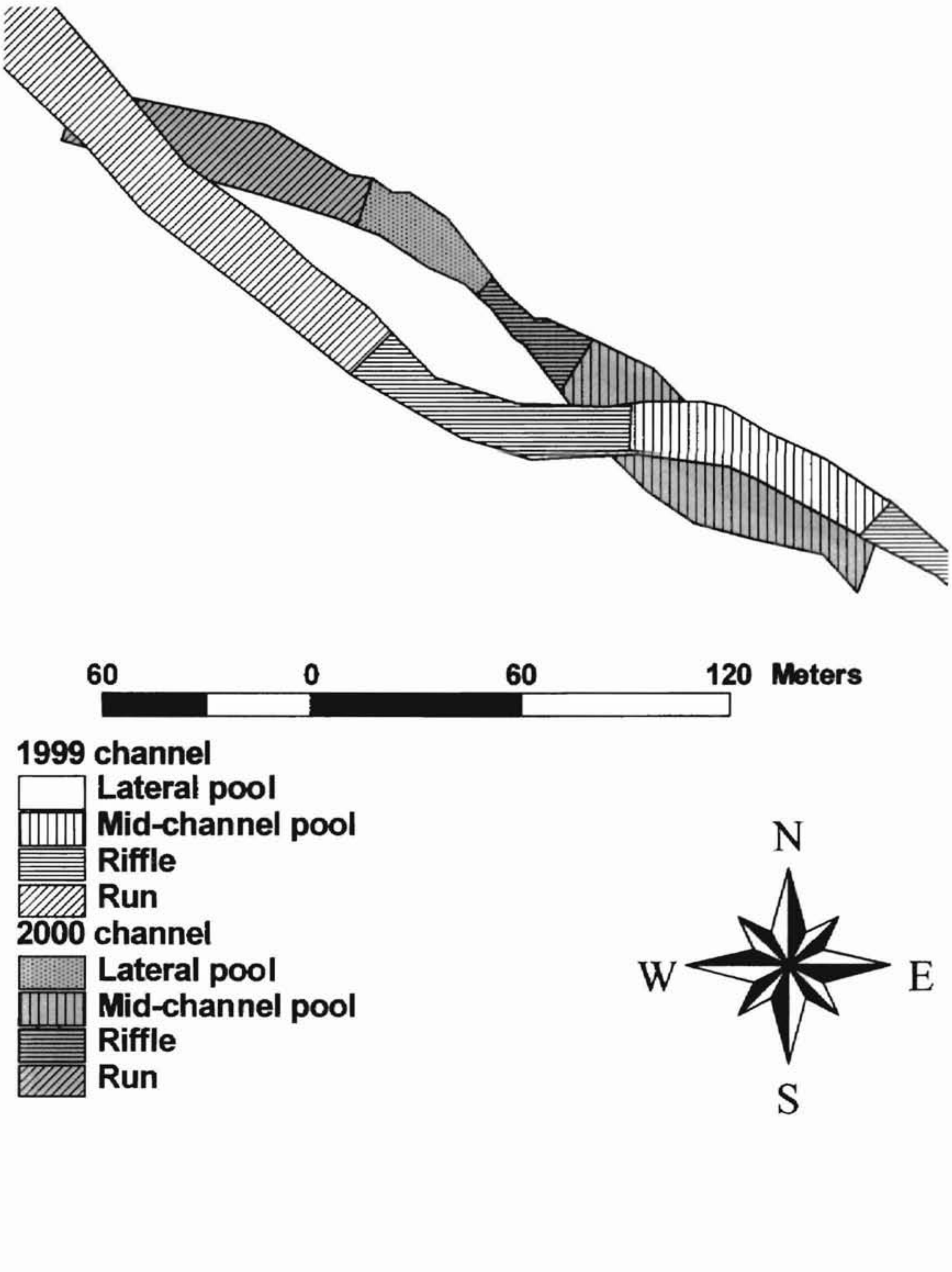
Site 2 Lateral Pool



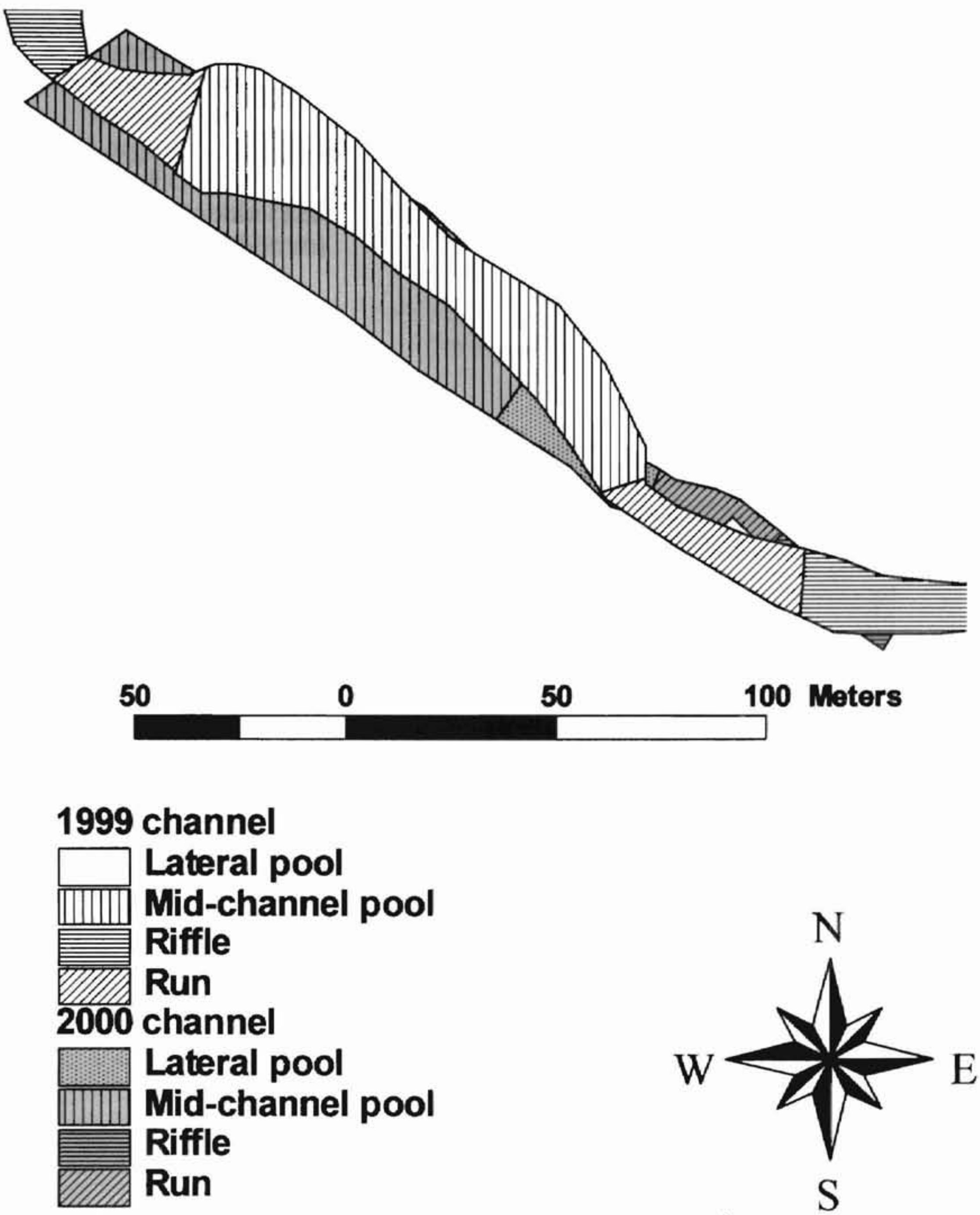
Site 1
Eldon Bridge



Site 3
Christie Bridge



Site 2
Baron Fork Ranch



Appendix A. Channel index codes used in classifying substrate and cover variables

Substrate

1	Organic Detritus
2	Vegetation (Aquatic)
3	Clay
4	Silt
5	Sand
6	Small Gravel (2-8mm)
7	Medium Gravel (8-16mm)
8	Large Gravel (16-64mm)
9	Small Cobble (64-128mm)
10	Large Cobble (128-256mm)
11	Boulder (>256mm)
12	Bedrock
13	Fractured Bedrock

Cover

0	No Cover
1	Undercut Bank
2	Bedrock (Fractured)
3	Log
4	Rootwad
5	Vegetation

Appendix B. Stream mesohabitat classification types and definitions adapted from Hawkins et al. (1993).

Riffle - Shallow reaches (<0.2 meters) with swiftly flowing, turbulent water with some partially exposed substrate. Medium to high gradient, substrate is usually dominated with medium gravel to small cobble.

Run - Swiftly flowing reaches with little surface agitation and may contain flow obstructions such as rootwads or boulders. Generally moderate depth 0.2-0.50 meters and may appear as a flooded riffle. Typical substrates are gravel, cobble, and boulders.

Lateral Pool - Formed by flow impinging against one streambank or against a partial channel obstruction. The associated scour is generally confined to <60% of wetted channel width. Channel obstructions include rootwads, woody debris, boulders and bedrock.

Mid-Channel Pool - Large pools formed by mid-channel scour. The scour hole encompasses more than 60% of the wetted channel. Water velocity is slow, and the substrate is highly variable.

Backwater - Found outside the average channel margins and caused by obstructions such as woody debris or cut-off channels. These areas are variable in depth and are dominated by fine-grain substrates and low current velocities. May be associated with gravel bars.

Appendix C. Velocity habitat suitability criteria (HSC) for smallmouth bass from current study (indicated in bold) and comparable studies for young of year (YOY), juvenile, and adults including Glover Creek, OK (Orth et al. 1981); the West Deerfield River, MA (Bain 1982); Upper James River, VA (Leonard et al. 1986); the Huron River, MI (Monahan 1991); the North Anna River and Craig Creek, VA (Groshens and Orth 1994); Wet Beaver Creek, AZ (Barrett and Maughan 1995): and Cacapon River, Greenbrier River, and Knapp Creek, WV (Newcomb et al. 1995).

Site location	Fish length (cm)/ size class	Optimal range SI=1.0 (cm/s)	Suitable range SI=>0.10(cm/s)
Upper James River, VA	**YOY**	6-18	0-30
West Deerfield River, MA	<8	3-7	0-10
Cacapon River, WV	<8	1-7	0-28
Greenbrier River, WV	<8	0-5	0-20
Knapp Creek, WV	<8	0-11	0-26
Huron River, MI	<11	10-46	0-76
Baron Fork Creek, OK	**<11.5**	**25-80**	**0-105**
Glover Creek, OK	<15	10-20	0-59
Wet Beaver Creek, AZ	<20	0	0-58
Upper James River, VA	**Juvenile**	9-18	0-55
West Deerfield River, MA	8-22.5	3-7	0-31
Huron River, MI	11-20	23-54	0-89
North Anna River, VA	10-20	4-45(1.0=24)[a]	0-82
Craig Creek, VA	10-20	7-50(1.0=17)[a]	0-80
Cacapon River, WV	>8	4-18	0-37
Greenbrier River, WV	>8	5-16	0-32
Knapp Creek, WV	>8	0-7	0-19
Upper James River, VA	**Adult**	10-19	0-36
Baron Fork Creek, OK	**>11.5**	**10-30**	**0-40**
Glover Creek, OK	>15	0-5	0-35
North Anna River, VA	>19.9	2-19 (1.0=3.5)[a]	0-70
Craig Creek, VA	>19.9	11-19 (1.0=13.5)[a]	0-32
Wet Beaver Creek, AZ	>20	0	0-40
Huron River, MI	>20	12-43	0-88
West Deerfield River, MA	>22.5	3-7	0-10

[a] Optimal criteria presented in the study as the range of suitability index (SI) between 0.7 and 1.0

Appendix D. Depth habitat suitability criteria (HSC) for smallmouth bass from comparable studies cited in Appendix C.

Site location	Length(cm)/ size class	Optimal SI=1.0 (m)	Suitable SI=>0.10(m)
Upper James River, VA	**YOY**	0.40-0.90	0.12-1.90
West Deerfield River, MA	<8	0.21-0.31	0.17-0.84
Cacapon River, WV	<8	0.40-0.80	0.20-1.10
Greenbrier River, WV	<8	0.30-0.60	0.10-0.90
Knapp Creek, WV	<8	0.20-0.40	0.10-0.60
Huron River, MI	<11	0.46-0.85	0.18-1.83
Baron Fork Creek, OK	**<11.5**	**0.35-1.15**	**0.05-1.50**
Glover Creek, OK	<15	0.10-0.20	0.10-0.98
Wet Beaver Creek, AZ	<20	0.60	0.20-1.80
Upper James River, VA	**Juvenile**	>0.65	>0.24
Huron River, MI	11-20	0.70-1.10	0.40-1.92
North Anna River, VA	10-20	0.40-0.76(1.0=0.55)[a]	0.18-1.70
Craig Creek, VA	10-20	1.08-1.20(1.0=1.14)[a]	0.20-1.50
West Deerfield River, MA	8-22.5	1.50-1.73	0.46-1.79
Cacapon River, WV	>8	0.53-1.00	0.25-1.70
Greenbrier River, WV	>8	0.40-0.70	0.18-0.88
Knapp Creek, WV	>8	0.65-0.70	0.50-1.20
Upper James River, VA	**Adult**	>0.85	0.40
Baron Fork Creek, OK	**>11.5**	**0.50-1.55**	**0.05-2.00**
Glover Creek, OK	>15	0.40-1.08	0.11-1.40
North Anna River, VA	>19.9	1.06-1.29(1.0=1.15)[a]	0.40-1.70
Craig Creek, VA	>19.9	1.13-1.37(1.0=1.28)[a]	0.50-1.62
Wet Beaver Creek, AZ	>20	1.30	0.30-2.70
Huron River, MI	>20	0.85-1.50	0.43-3.67
West Deerfield River, MA	>22.5	1.60-1.78	0.87-1.91

[a] Optimal criteria presented in the study as the range of suitability index (SI) between 0.7 and 1.0.

VITA γ

William Jason Remshardt

Candidate for the Degree of

Master of Science

Thesis: EFFECTS OF STREAMFLOW VARIATION ON SMALLMOUTH BASS HABITAT IN AN ALLUVIAL STREAM

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