ABSTRACT

READ, ALESIA N. Characterizing American Shad Spawning Habitat in the Upper Roanoke River Basin, Virginia.
(Under the direction of Joseph E. Hightower)

Populations of American shad (*Alosa sapidissima*) have declined from historical levels due to overfishing, decreased water quality and habitat losses including those due to dam construction. One approach for restoring these populations is to identify suitable habitat upstream of dams that could be restored through dam removal or by providing fish passage. The goal of this research is to identify and characterize potential spawning habitat for American shad in the upper Roanoke River basin of Virginia, above Kerr Reservoir. Five mainstem rivers that are upstream of the Roanoke Rapids, Gaston, and Kerr dams (Big Otter, Staunton, Banister, Dan, Hyco) were the focus of this research. Roanoke Rapids Dam is the first obstruction to American shad spawning migration in the Roanoke River basin, and just completed the FERC (Federal Energy Regulatory Commission) relicensing process in 2004. One of the provisions of the new license is to evaluate a trap and transport program for spawning American shad. Characterizing the habitat above the dam, in terms of suitability, is an important step in predicting the benefits of fish passage.

A detailed physical habitat assessment, including monthly water quality monitoring, indicated that the Banister and Hyco rivers consistently had lower dissolved oxygen concentrations and may provide lower quality habitat for American shad compared to the other rivers. However, according to the current published Habitat Suitability Index (HSI) model, which incorporates surface water temperature and current velocity as criteria for suitable habitat, the five rivers appear to contain suitable habitat with HSI values ranging from 0.83 to 1.00 during May. I constructed a modified HSI model with surface water temperature and current velocity, as well as dissolved oxygen, pH and a component for substrate composition. The modified model suggested that the Big Otter and

Staunton rivers would provide the highest quality spawning habitat for American shad because of the presence of gravel, cobble and bedrock substrates. Larger substrates have been suggested to be preferred over smaller substrates by spawning adult American shad in the Neuse River, NC.

Egg incubation experiments were conducted during the American shad spawning season, from mid-April to the end of May 2004, throughout the basin. Hatching success from incubation experiments was relatively high (69-94 percent). No significant differences ($p<0.05$) among incubation sites were found in terms of hatching success, which suggests that water quality throughout the basin is suitable for egg development.

The combination of field data and habitat suitability modeling used to predict habitat quality was an efficient approach for assessing habitat and could be used by planners and managers working to restore American shad populations in other river systems. Results from the physical habitat assessment, the habitat suitability modeling and the egg incubation results suggest that a trap and transport program should be successful for spawning American shad in the Roanoke basin.

CHARACTERIZING AMERICAN SHAD SPAWNING HABITAT IN THE UPPER ROANOKE RIVER BASIN, VIRGINIA

by

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DEDICATION

To my parents---

Thank you for the acceptance, the support, and for the endless encouragement. You are truly my foundation.

BIOGRAPHY

Alesia Noelle Read was born on December 7, 1975 in Kingston, New York. Her family spent most summers in Jamestown, Rhode Island on the water. Alesia graduated high school in June 1994 with hopes of becoming a scientist (which kind, she was not sure). When she entered the University of North Carolina at Chapel Hill the following fall she soon realized that the sciences were wide and varied. She soon started taking electives in Marine Science. She went on a study abroad program called Arctic Biology, in Reykjavik, Iceland, where she saw first hand what an economy based on fisheries was all about. Alesia soon decided that fisheries was the path to pursue, and received a fellowship working at the Institute of Marine Sciences working on larval mortality. Alesia graduated with a Bachelor of Science in Biology from UNC-CH (GO HEELS!) in 1998. She went down south for an internship, and later a paid position, working with Mote Marine Laboratory in Sarasota, Florida in the Fisheries Department. It was at Mote that her interest in fisheries science was solidified and she realized she wanted to pursue a graduate degree. Good old NC State University (GO WOLFPACK?!) had a great Fisheries and Wildlife program, so that was perfect. After taking several classes with Dr. Joe Hightower, and discussing similar project interests, they proposed a Master's project working on characterizing spawning habitat for American shad. Her time at NC State has been rewarding and enriching. Alesia has accepted a fellowship working with the American Fisheries Society headquarters in Bethesda, MD. She will be helping to coordinate a symposium on cooperative fisheries management and research for their annual meeting that will take place in Anchorage, Alaska! After that…too many adventures, too little time.

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INTRODUCTION

Historically, American shad (*Alosa sapidissima*) supported an important commercial fishery along the Atlantic Coast (Walburg and Nichols 1967). American shad were reported to spawn in the upper reaches of virtually every river along the eastern seaboard (Stevenson 1897). However, the commercial harvest peaked in the late 1800s (St. Pierre 1979) and populations have been steadily declining since that time. In fact, low abundances necessitated moratoria in Maryland (1980) and Virginia (1994) (Bilkovic et al. 2002).

Declines in American shad riverine abundance have been attributed to decreased water quality, habitat degradation, overfishing, and construction of hydroelectric dams (Mansueti and Kolb 1953; Chittenden 1976; Ross et al. 1993b). Access to suitable spawning areas is critical, and as many of the spawning grounds are located in river headwaters, it follows that obstructions blocking or limiting access to these important areas will have detrimental effects on reproduction and population abundance (Stevenson 1897). Provision for fish passage, including trap-and-transport, is one approach that can allow anadromous species to regain access to important spawning grounds. For example, a trap-and-transport program in the Susquehanna River provided American shad with initial access to important spawning grounds above a series of hydroelectric dams (Hendricks and St. Pierre 2002). The later construction of fish lifts allowed larger numbers of fish to move upstream, and spawning reportedly takes place between and above the four dams. Run size has increased considerably since the restoration program began in the 1950s, from about 26,000 fish in 1981 to hundreds of thousands in 2001 (Hendricks and St. Pierre 2002). A program for fish passage in the Roanoke basin would need to begin with an assessment of habitat quality, similar to the evaluations done in the upper Susquehanna basin prior to the start of that restoration program (Hendricks and St. Pierre 2002).

LIFE HISTORY

American shad are the largest members of the herring family. As an anadromous species, they spend most of their lives in the ocean but spawn in the upper reaches of coastal streams and rivers. Juvenile American shad grow during their migration toward the ocean where they spend 3-6 years before eventually returning to their natal streams to spawn (Leggett 1973). The timing of spawning migration for American shad is primarily governed by ocean temperature (Leggett 1973). An appropriate temperature regime during critical stages in American shad life history can improve year class strength, and ultimately abundance of stocks (Crecco and Blake 1983). American shad return to the headwaters of rivers and spawning begins when temperatures reach approximately 12°C and continues until exceeding 20°C (Leggett and Whitney 1972). This temperature "trigger" is the reason that spawning migrations occur later in the year at northern latitudes, as temperature increases are delayed. The percentage of American shad that die after spawning decreases from south to north (Leggett and Carscadden 1978). The apparent high mortality after spawning in southerly rivers could be due to increased metabolic demands caused by the synergism of prolonged elevated temperatures and the considerable energy expended during spawning activities (Leggett and Carscadden 1978).

American shad have been referred to as habitat generalists that spawn anywhere in rivers (Massmann 1952; Marcy 1972) with few essential habitat requirements other than temperature and current velocity (Stier and Crance 1985). However, other recent studies have shown that several habitat variables in addition to temperature and current velocity may influence spawning habitat suitability, including substrate composition, dissolved oxygen, pH, and possibly turbidity (Dadswell et al. 1983; Ross et al. 1993b; Beasley and Hightower 2000; Bowman and Hightower 2001; Bilkovic et al. 2002). The number of habitat variables that determine favorable spawning grounds is not known, as these variables are often correlated. It is more likely a suite of factors that influences selection of spawning locations by American shad.

STUDY AREA

McDonald (1884) reported that the maximum distance migrated by an American shad in the Roanoke River Basin, within North Carolina and Virginia was to Salem, Virginia (river kilometer [rkm] 557; Figure 1). A dam has been present at Roanoke Rapids (rkm 221) since the early 1900s (Hightower et al. 1996). It was replaced in 1955 by the 22-m-high Roanoke Rapids Dam, which generates hydroelectric power. Neither dam was built with fish passage provisions; therefore this site has for over a century marked the upstream limit to the spawning migration for American shad and all other anadromous species in the basin (Figure 1). Gaston Dam (rkm 233), constructed in 1963, and Kerr Dam (rkm 288), constructed in 1953, are the next dams upstream of Roanoke Rapids Dam.

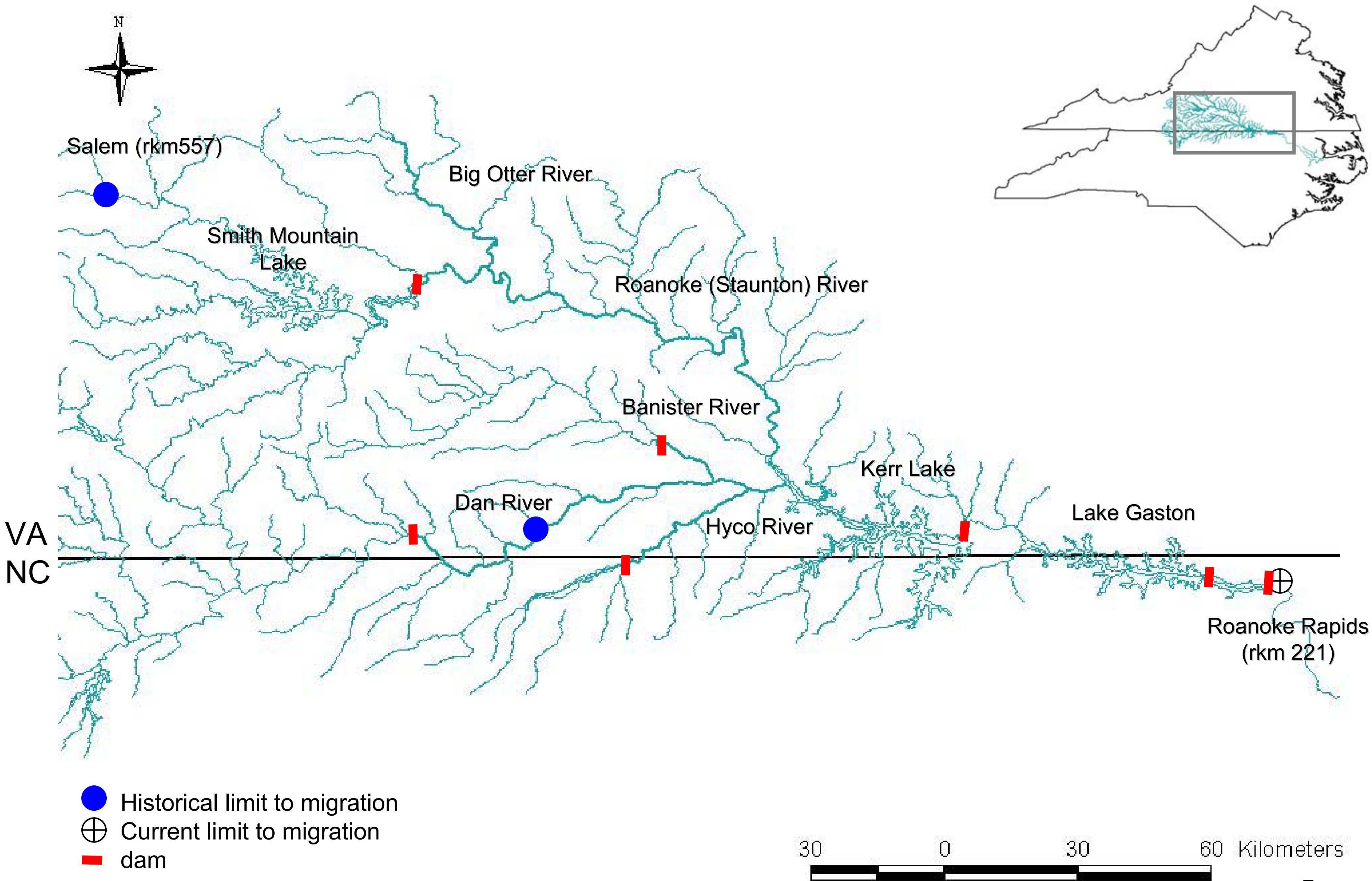
It has been suggested that the dam at Roanoke Rapids blocks access to potentially suitable spawning habitat, therefore limiting reproductive success of American shad (Hightower and Sparks 2003). Roanoke Rapids Dam and Gaston Dam recently underwent the FERC (Federal Energy Regulatory Commission) relicensing process, completed in 2004. Built into the new license is an experimental trap-and-transport program for American shad to be transported from below Roanoke Rapids Dam to the rivers above Kerr Lake. When American shad are transported above Kerr Lake, they will regain access to over 400 rkm of potentially suitable mainstem habitat above Kerr Lake (USEPA 2001), or 63% more mainstem habitat than is available to them now. Characterizing the five mainstem rivers above Kerr Lake for suitability as American shad spawning habitat will provide useful information to agencies involved in the trap-and-transport project and contribute to the successful reintroduction of American shad into historically utilized spawning grounds.

This study will address habitat quality in the part of the Roanoke River basin between Kerr Lake and the first upstream dam on each of the major rivers (Figure 1). Based on Geographic Information System (GIS) data obtained from BASINS (Better Assessment Science Integrating Point and Nonpoint Sources, USEPA 2001), there is an estimated 133 rkm of potential mainstem habitat on the Staunton River between the upper end of Kerr Lake and Leesville Dam. The only relatively large tributary on this section of the Staunton is the Big Otter River, which has at least 40 rkm of potential habitat, based on the distance to where the river narrows to a width of 30 m. The Dan River contains 79 rkm of mainstem habitat between the upper end of Kerr Lake and the first dam at Danville (Brantly Steam Plant Dam). The Banister River, which is a tributary to the Dan, contains 17 rkm of habitat below the first dam (Halifax Dam). The Hyco River, which is also a tributary to the Dan, contains 30 rkm of habitat downstream of its first dam (Afterbay Dam).

OBJECTIVES

1. To conduct a detailed physical habitat assessment of the rivers within the Roanoke River basin above Kerr Lake, inventorying habitat based on microhabitat physical parameters and larger scale geomorphological characteristics.
2. To evaluate the rivers above Kerr Lake using both the published (Stier and Crance 1985) and modified versions of Habitat Suitability Index (HSI) models to rank reaches for potential spawning habitat value or quality.
3. To conduct egg incubation experiments in the rivers above Kerr Lake to evaluate hatching success based on water quality.

Figure 1. Map of Roanoke River Basin with historical (blue) and current (white) limits to spawning migration represented by crosshatched circles. The lowermost dam on each river is represented by a red bar.



CHAPTER ONE

Habitat Assessment of the Roanoke River Basin above Kerr Lake

INTRODUCTION

Essential Fish Habitat is defined in the Magnuson-Stevens Act (16 U.S.C. 1801 et seq.) as the waters and substrate necessary for spawning, breeding, feeding, or growth to maturity of fish. It follows from this Act that there is an important relationship between specific life stages of fish and the habitat that they need in order to develop and reproduce. These relationships are particularly evident for anadromous fishes such as striped bass (*Morone saxatilis*) and American shad (*Alosa sapidissima*) that spawn in coastal rivers but live in marine water as adults. Dam construction may limit their access to historical spawning grounds and cause changes in flow or water quality that limit reproduction. Objectives for this part of the project were to delimit and characterize the habitat above Kerr Lake (Figure 1, Introduction) in terms of potentially suitable spawning habitat for American shad.

Habitat Suitability Index (HSI) models were originally developed to facilitate impact assessment, habitat management, and project planning (U.S. Fish and Wildlife Service 1980). These models provide a way to rank or score habitats and should be viewed as hypotheses of species-habitat relationships rather than proven cause and effect relationships. Their value is to serve as a basis for improved decision-making and increased understanding of habitat relationships because they make specific predictions about habitat relationships that can be tested and refined (Stier and Crance 1985). The Habitat Suitability Index Modeling Program is part of the Habitat Evaluation Procedures set forth by the U.S. Fish and Wildlife Service in the early 1980s.

HSI models are used to quantify habitat quality on a scale between 0 (unsuitable) and 1 (optimal) based on criteria that have been proposed as important for a particular species and life stage. For American shad, Suitability Index (SI) curves have been developed for spawning adults, eggs and larvae, and juveniles (Stier and Crance 1985; Ross et al. 1993a; Ross et al. 1993b; Bilkovic et al. 2002). Stier and Crance (1985) developed the original American shad HSI model using the Delphi technique, which is a subjective technique based on expert opinion regarding appropriate ranges for habitat variables.

The parameters proposed as important for the American shad HSI model were water temperature and current velocity for spawning adults and water temperature only for eggs and larval develpment. Ross et al. (1993a) field-tested the Stier and Crance (1985) model and generally found results consistent with their model. Ross et al. (1993a) suggested that the optimal upper limit for spawning temperature should be increased from 20°C to 24.5°C. They also suggested that the upper limit for optimal temperature for egg and larval development be increased from 25.0°C to 26.5°C. Bilkovic et al. (2002) constructed a detailed habitat model for American shad suitability, including additional parameters (dissolved oxygen, pH, salinity, secchi depth, river depth, substrate composition, and others). Bilkovic et al. (2002) agreed with the increase in the upper thermal limit to 24.5°C suggested by Ross et al. (1993a). For current velocity, Bilkovic et al. (2002) used the lower optimal limit from the Stier and Crance (1985) model (0.3 m/s) and the upper limit (0.7 m/s) proposed by Ross et al. (1993a).

Additional parameters (substrate composition, dissolved oxygen, and pH) have been suggested as useful additions to the Stier and Crance (1985) HSI model. For example, several studies have shown a higher frequency of American shad spawning activity occurring over coarser substrates consisting of gravel, cobble and boulder regardless of the greater abundances of sand and silt substrates available in the same reaches (Beasley and Hightower 2000; Bowman and Hightower 2001; Hightower and Sparks 2003). Dissolved oxygen could be an important variable to include in habitat models in areas where low dissolved oxygen levels regularly occur. A minimum of 5 mg/L of dissolved oxygen is the recommended concentration for optimal habitat (Walburg and Nichols 1967; Marcy 1972; Stier and Crance 1985; Ross et al. 1993a; Bilkovic et al. 2002). pH could also be a useful variable for areas that encounter extreme pH fluctuations. Bilkovic et al. (2002) suggested an optimal range for pH of 6.0-9.9.

Habitat assessment on a larger scale (e.g. longitudinal classification into run, riffle, pool) may also be useful for assessing American shad habitat suitability. Kynard et al. (2000) suggested that use of large-scale habitat classification to document habitat use and preference can lead to a broader understanding of the relationship between a fish and its habitat than simply documenting microhabitat alone. Ross et al. (1993b) observed the greatest amount of American shad spawning activity in run habitat and the lowest in pools in the upper Delaware River. The combination of swift and shallow water present in runs could translate into higher survival of newly spawned eggs (Ross et al. 1993b). Another factor that could increase survival is that there may be fewer egg predators in run habitats (Ross et al. 1993b). Observations of spawning activity on the Neuse River and collections of American shad eggs on the lower Roanoke River may also suggested the preference for swift and shallow waters (Beasley and Hightower 2000; Bowman and Hightower 2001; Hightower and Sparks 2003).

METHODS

Habitat Assessment

Based on an extensive literature review (Table 1), six microhabitat water quality and hydrological parameters (dissolved oxygen, temperature, pH, turbidity, current velocity, and conductivity) were chosen for monitoring during the 2003 field season. I also collected data on presence or absence of woody debris and percent overhanging vegetation because those variables have been suggested as meaningful large-scale habitat variables for American shad in the Mattaponi and Pamunkey rivers in Virginia (Bilkovic et al. 2002).

Habitat data were collected approximately once every river kilometer along the Staunton (Roanoke), Big Otter, Banister, Hyco, and Dan rivers where navigable by 16-foot johnboat, until the lowermost dam was reached on each river (Figure 1). A handheld GPS receiver was used to estimate the 1-km distance between sampling sites. Sampling was completed over four months from July to October 2003. The southern 23.8 rkm portion of the upper Hyco River and the entire Banister River were not navigable because of large downed trees obstructing the pathway. The Big Otter River was also not navigable because it was too shallow. Therefore, data were collected at road crossings in these non-navigable waters to complete the survey in these areas.

At each sampling location, I recorded the location using UTM coordinates (WGS 1984 datum; zone 17). I anchored the boat at mid-channel and measured the width of the river with a handheld rangefinder and depth with a 2.0-meter long depth rod. Surface dissolved oxygen (mg/L), water temperature (°C), and conductivity (µS) were measured using a YSI 85 multiprobe instrument (Yellow Springs Instruments, Yellow Springs, Ohio). pH was measured using a handheld waterproof pH meter (Extech PH100). Turbidity was measured in nephelometric units (ntu) using a 2100P portable field turbidimeter (Hach Company). Current velocity (m/s) was recorded at 0.6 of the water depth using a Marsh-McBirney Model 201D.

Two bottom samples were taken from either side of the boat using a Petite Ponar bottom sampler. Sediment particle size was determined using the modified Wentworth (1922) particle scale ranking system (Schaffter 1997; Table 3). The presence or absence of large woody debris within approximately a 2-m radius was recorded when visible at the sampling location where the boat was anchored. Percent overhang, in terms of overhanging tree canopy or vegetation, was visually estimated and recorded as the percentage of river shaded by overhanging vegetation (Bilkovic et al. 2002). The longitudinal classification scheme of each river segment was determined using a combination of criteria outlined in Ross et al. (1993b) and Kynard et al. (2000) (Table 2).

Circuit Sampling

I collected 181 of the 227 habitat data points in July but the remaining points were collected in October due to difficulty in navigating the rivers.

Because some environmental conditions changed substantially over that period, it would not be appropriate to compare values such as turbidity or dissolved oxygen among the 227 sites. For that reason, and because I was interested in water quality during the spring spawning season, I carried out additional sampling “circuits” at 23 sites 50-100 m upstream of selected road crossings (Figure 2). These circuits could be completed in two days, and provided a temporal snapshot of conditions that could be compared among rivers. Circuit sampling was conducted monthly from October 2003 to August 2004 (Appendices I-VI). Dissolved oxygen (mg/L), temperature (°C), conductivity (µS), turbidity (ntu), pH, and current velocity (m/s) were measured and recorded. The same methods were used to collect data as used in the initial point sampling, but these measurements were done without a boat; therefore, measurements were taken closer to the riverbank. Historical and mean daily discharge volumes were obtained from United States Geological Survey (USGS) gaging stations near several of the circuit sampling locations to compare discharge on the days when circuit sampling was conducted with historic means for that day. An analysis of variance was used to detect differences among rivers in water quality parameters for data collected during circuit sampling.

Habitat Suitability Index Models

Historical current velocity data from USGS gaging stations and temperature data from Virginia Department of Environmental Quality (VADEQ) Water Quality Monitoring Stations were obtained for the months of April through June for ten sites within the Roanoke River Basin. Overall riverine HSI values were calculated using these historical data. I also examined habitat suitability using current velocity and temperature data collected during circuit sampling in March, April, May and June. The rivers were divided into segments corresponding with circuit sampling sites, these segments were then used to estimate the approximate length (rkm) of suitable habitat during the months of spawning season. Habitat suitability was estimated using the original Stier and

Crance (1985) HSI model, as well as two proposed alternatives that include a component for substrate composition. Although dissolved oxygen and pH are potentially critical water quality variables, they were not included in a modified HSI model because all measured values for both variables in my study fell within the optimal ranges for spawning adults and egg and larval development.

Model 1

Model 1 is the default HSI model defined by Stier and Crance (1985) (Figure 3) using temperature (optimal range,14-20°C) and current velocity (optimal range, 0.31-0.91 m/s) for spawning adults and temperature (optimal range, 15-26°C) only for egg and larval development to calculate overall HSI values.

Model 2

Model 2 used the current velocity range as defined by Stier and Crance (1985), a single optimal temperature range (14.5-24.5 °C) for both spawning adults and egg and larval development (Ross et al. 1993a; Bilkovic et al. 2002) and a suitability curve for substrate, which was taken from the IFIM (Instream Flow Incremental Methodology) model developed by Stier and Crance (1985) to calculate HSI values (Figure 4).

Model 3

Model 3 used the same current velocity range and temperature range as in model 2, but a different suitability curve for substrate developed from two studies done in the Neuse River basin (Beasley and Hightower 2000; Bowman and Hightower 2001) to calculate HSI values (Figure 4).

RESULTS

Habitat Assessment

Habitat monitoring in 2003 began on July 3 and was completed on October 21. Most of the variability among rivers in temporally varying parameters such as temperature and dissolved oxygen would likely be explained by natural changes in environmental conditions over time. Therefore, ranges are presented for each river but differences among rivers were not tested using statistical methods. Means, standard errors and ranges are presented in Table 4.

Big Otter River

Seven locations were sampled on the Big Otter River during October 2003 over a 40-rkm section from the confluence with the Staunton River to where the river width narrowed to less than 31 m. Water quality variables were within expected ranges for October (10.9-11.9 mg/L for dissolved oxygen, 11.0-12.0 °C for temperature, 7.3-7.7 for pH, 2.5-10.2 ntu for turbidity, 0.2-0.6 m/s for current velocity, and 54.7-89.7 µS for conductivity). Width ranged from 9-31 m, and depth ranged from 0.3-1.3 m (Table 4). Larger substrates such as bedrock, boulder, cobble and gravel occurred at most sites (Figure 5). Riffles were encountered at five of the seven sites, and most sites contained woody debris and had at least some overhanging vegetation (Figures 6-8).

Staunton River

Eighty percent of the 130 data points for the Staunton River were collected during July 2003, with the remainder collected during October 2003. A total of 133 rkm was surveyed on the Staunton from Kerr Lake to Leesville Dam. For the data collected during July, dissolved oxygen ranged from 5.3-7.9 mg/L, temperature ranged from 21.4-25.2 °C, pH ranged from 7.0-8.6, turbidity values were between 5.8 and 48.6 ntu, current velocity values were between 0.2 and 2.0 m/s, and conductivity ranged from 147.5-188.8 µS. Data collected during October were also within expected ranges (8.0-11.5 mg/L for dissolved oxygen, 15.6-19.7 °C for temperature, 7.0-7.6 for pH, 3.1-12.5 ntu for turbidity, 0.0-1.2 m/s for current velocity, and 131.9-138.6 µS for conductivity). Width ranged from 31-124 m and depth ranged from 0.3-4.8 m (Table 4). Bottom substrates were mostly gravel, cobble, boulder, and bedrock above Brookneal and mostly sand below that point (Figure 5). Eighty-five percent of the river was classified as run habitat and the rest was mostly riffle habitat (Figure 6). Visible woody debris was recorded at only 13% of the sampling points and overhang percentage was almost entirely 1-25% (Figures 7-8).

Banister River

Four locations were sampled on the Banister River during October 2003 over a 17-rkm section from the confluence with the Dan River to Halifax Dam. Water quality measurements were within expected ranges (6.9-7.3 mg/L for dissolved oxygen, 16.2-16.9 °C for temperature, 7.0-7.2 for pH, 35.5-40.1 ntu for turbidity, 0.1-0.3 m/s for current velocity, and 70.5-73.1 µS for conductivity). Width ranged from 26-34 m, and depth was between 0.5-1.1 m (Table 4). Bottom substrate for the four sampling locations consisted of sand, silt/clay, and boulder (Figure 5). The entire river was classified as run habitat (Figure 6). Visible woody debris was recorded at 3 of the 4 sampling locations and most of the river was classified as 26-50% overhang (Figures 7-8).

Dan River

Sixty-eight data points were sampled over a 79-rkm section of the Dan River from Kerr Lake to the first low-head dam in Danville, VA during July 2003. Other than two dissolved oxygen readings below the 5.0 mg/L minimum, water quality parameters were within expected ranges (4.7-9.5 mg/L for dissolved oxygen, 21.3-26.5 °C for temperature, 7.0-7.8 for pH, 41.5-611.0 ntu for turbidity, 0.4-1.6 m/s for current velocity, and 56.2-111.3 µS for conductivity). Width was between 43 and 131 m, and depth ranged from 1.0 to 4.3 m (Table 4). Bottom substrate on the Dan River consisted of mostly sand (Figure 5). Ninety-eight percent of the river was classified as run habitat (Figure 6). Visible woody debris was recorded at only 12 of the 68 sampling locations and 98.5% of the river was classified as 1-25% overhang (Figures 7-8).

Hyco River

Eighteen locations were sampled over a 30-rkm section of the Hyco River from the confluence with the Dan River (almost at Kerr Lake) to Afterbay Dam. Half of the sites were sampled during July 2003 and the other half were sampled during October 2003. Water quality data collected during July were within accepted ranges except that all 10 dissolved oxygen readings were below the 5.0

mg/L minimum (3.4-4.9 mg/L for dissolved oxygen, 26.9-27.8 °C for temperature, 6.0-6.8 for pH, 17.1-20.9 ntu for turbidity, 0.0-0.2 m/s for current velocity, and 102.2-110.4 μS for conductivity). Water quality data collected during October were 6.5-7.4 mg/L for dissolved oxygen, 17.7-18.5°C for temperature, 6.5-7.4 for pH, 5.2-7.8 ntu for turbidity, 0.0-0.5 m/s for current velocity, and 96.8-108.8 μS for conductivity. Width ranged from 17 m at the uppermost site sampled to 296 m at the confluence with the Dan where it enters Kerr Lake, and the depth ranged from 0.8-6.8 m (Table 4). Bottom substrate consisted of silt/clay, sand, gravel, cobble, or bedrock (Figure 5). Ninety-four percent of the river was classified as run habitat (Figure 6). Visible woody debris was recorded at 89% of the sampling locations and half of the river was classified as 1-25% overhang and the other half was 26-50% overhang (Figures 7-8).

Circuit Sampling

Circuit sampling was initiated because there was a need to compare habitat variables within and among rivers. Circuits were completed once each month from October 2003 through August 2004. Twenty-three sampling sites were visited during each two-day sampling occasion (Figure 2). River discharge volumes on dates when circuit sampling was done were often similar to historical means but some extremes were encountered (Figure 9). For example, flows were relatively low in January and March 2004 and above average in April and June.

There were significant differences ($p<0.05$) among rivers for all water quality parameters measured during circuit sampling, except for turbidity, which was marginally significant ($P=0.06$). Differences among rivers were generally not large except for conductivity, which was consistently lower for the Banister and Big Otter rivers (Figure 10). Water temperature was significantly lower and dissolved oxygen was significantly higher for the Big Otter River compared to the other rivers. Dissolved oxygen levels were significantly lower for the Hyco and Banister rivers compared to the remaining rivers. The primary factor regulating dissolved oxygen levels appeared to be water temperature (Figure 11). Levels below 5 mg/L were not encountered until water temperatures were above 26 °C. The pH values were typically within a narrow range between 6.5 and 7.5 for all months, although pH in the Staunton River was significantly higher than for the other rivers. Mean current velocities ranged from 0.32 to 0.51 m/s for the five rivers, with significantly higher velocities for the Big Otter (0.49 m/s) and Dan (0.51 m/s) rivers than the others. Turbidity levels were generally low during the winter months but increased during spring and summer periods of high flow.

Habitat Suitability Index Models

HSI calculations using historical data

Based on historical data from USGS and VADEQ water quality monitoring stations, optimal water temperature for spawning occurred during April-May (Table 5). Current velocities were almost always within the optimal ranges during all four months (Table 6). Water temperatures for egg and larval development were within the optimal range at most sites in April and all sites during May-June (Table 7). Combined HSI scores for riverine life stage were highest for April-May (Table 8). HSI calculations using data from the 23 circuit sites were generally similar to those from USGS and VADEQ data but provided greater spatial resolution given that there were more sampling sites.

Model 1

Using model 1 to rank habitat for suitability with an arbitrary cut-off value of 0.60, the greatest amount of suitable habitat is available in May (103 rkm), on the Big Otter and Staunton rivers (Table 9). Optimal water temperatures for spawning occurred in between the April and May samples (Table 10). Current velocity was generally within the optimal range (Table 11; Figures 12-15) except that velocity was often near 0 m/s on the Staunton River below Leesville Dam (site 5) and at the lowermost Hyco River site (site 20). Water temperatures were generally within the optimal ranges for egg and larval development during May-June (Table 12). Overall riverine HSI values were somewhat low and variable (Table 13; Figures 16-19) because the optimal temperatures for spawning occurred between the April and May circuits. Some HSI values remained high in June at the northern circuit sites, due to cooler temperatures compared to the southern river sites.

Model 2

Based on the revised temperature range for spawning and egg and larval development, water temperatures were generally within the optimal range during May-June (Table 14). High suitability values were calculated for substrate using the IFIM suitability curve because of the high score assigned to sand (Table 15, Figure 20). The resulting overall suitability values were low in March and April due to cool temperatures but relatively high throughout the basin in May-June (Table 16, Figures 21-24). Using model 2 to rank habitat for suitability with a cut-off value of 0.60, the greatest amount of suitable habitat is available in June (219 rkm), with suitable habitat found on all rivers except the Hyco River (Table 9).

Model 3

Suitability values for bottom substrate were considerably lower at many sites because of the prevalence of sand (Table 17, Figure 25). Sand is not scored highly using the model 3 substrate suitability curve (0.2). Estimated suitability was highest in sections of the Staunton (near Long Island) and Big Otter rivers where cobble, boulder and bedrock substrates occurred. Overall suitability tended to be highest in May and in the Staunton and Big Otter Rivers (Table 18, Figures 26-29). Using model 3 to rank habitat for suitability with a cut-off value of 0.60, the greatest amount of suitable habitat is available in May (62 rkm), on the Big Otter and Staunton rivers (Table 9).

Comparison of Alternative Models

Suitability index values for model 1 were generally similar among sites with gradually increasing values across months that reflected increasing spring temperatures (Figure 30). Model 2 HSI values were optimal for most sites because (like model 3) a wider range for optimal temperatures was assumed and (unlike model 3) because most substrates were assumed to provide optimal spawning habitat. For model 3, HSI values were low for most sites because of the low SI score assigned to sand substrate.

DISCUSSION

Findings from this research suggest that there is a considerable amount of suitable habitat above Kerr Reservoir. The most important factor in determining the amount of suitable habitat is the assumed value of different substrates for spawning, especially sand. All habitat variables evaluated were within suitable ranges at some point during the spawning migration. Based on model 3, the most conservative model, habitat model output suggests there are at least 62 rkm of suitable habitat in May and 39 rkm in June.

Dissolved Oxygen

Depletion of dissolved oxygen in rivers and streams can be caused by algal and microbial respiration associated with algal blooms; discharges from municipal and industrial wastewater treatment facilities; leaks and overflows from sewage lines and septic tanks; stormwater runoff from agricultural and urban land; and decaying vegetation (Bain 1999). Dissolved oxygen concentration in unpolluted waters is primarily and inversely related to temperature. Our results clearly illustrate this relationship and were similar among sites. Dissolved oxygen concentrations below 5 mg/L occurred only in summer months when temperatures increased beyond 26°C. Dissolved oxygen was below 5 mg/L for 12 of 365 measurements, only occurring late in July on the Dan and Hyco rivers. These dissolved oxygen concentrations below 5 mg/L were all recorded between the late morning and late afternoon, which suggests that diel fluctuation was not cause of the low observed levels. The 5 mg/L minimum dissolved oxygen concentration was specified by the USEPA (U.S. Environmental Protection Agency 1976, 1986) as a quality criterion for maintenance of aquatic biota. This dissolved oxygen threshold has also been recommended in numerous studies as the acceptable minimum for spawning adult American shad (Marcy 1972;

Walburg and Nichols 1967; Stier and Crance 1985; Ross et al. 1993a, b; Bilkovic et al. 2002).

Temperature

Temperature has long been suggested as the main factor controlling time of spawning for American shad, ensuring that adults arrive at the spawning grounds when temperatures are optimal for egg and larval survival (Leggett and Whitney 1972). Leim (1924) reported a minimum of 12°C for any American shad spawning activity to occur. Leggett (1973) reported that “optimum survival of shad eggs occurred at approximately 17°C,” and hatching and survival are at a maximum between 15.5 and 26.5°C. Marcy (1972) observed peak spawning activity in the lower Connecticut River between 14.8 and 22°C. Massmann (1952) reported the mean spawning temperature as between 16 and 17°C in some rivers in Virginia. Stier and Crance (1985) used a range of 14 to 20°C as optimal for spawning and 15.5 to 26.0°C as optimal for egg and larval development in their riverine habitat suitability index (HSI) model calculations. Ross et al. (1993a) reviewed the Stier and Crance HSI model, and suggested that the upper limit for optimal spawning temperature be increased to 24.5°C and the lower limit be raised to 14.5°C. Ross et al. (1993a) also suggested an increase to 26.5°C for the upper limit for optimal temperature for egg and larval development. Bilkovic et al. (2002) reviewed many of the above studies and suggested an optimum range for both spawning adults and egg and larval development of 14.5 to 24.5°C. Our results suggest that temperatures in March (mean 9.6°C) will be below the optimum range. Optimal temperatures for spawning and egg and larval development would likely be encountered sometime in April or May, although temperatures during June could remain suitable. Our estimates of suitability were somewhat crude because of the monthly interval between circuit samples. Improved results could be obtained by measuring temperatures more often; for example, logging temperature recorders could be used to estimate daily suitability values.

Current Velocity

Walburg and Nichols (1967) suggested that water velocities between 0.31 and 0.91 m/s were sufficient to eliminate silt deposits and would therefore be optimal for American shad spawning grounds. This range of velocities was assumed to be suitable in the Stier and Crance (1985) HSI model. Massmann (1952) observed spawning activity at velocities between 0 and 0.91 m/s in Virginia rivers. Ross et al. (1993a) observed spawning activity at velocities of 0 to 0.7 m/s in the Delaware River, and suggested that all velocities under 1 m/s would be appropriate for egg and larval development. Beasley and Hightower (2000) observed spawning activity at velocities between 0.06 and 1.28 m/s in the Neuse River. Bowman and Hightower (2001) also observed spawning activity in the Neuse River but at a narrower range (0.2-0.6 m/s). Hightower and Sparks (2003) reported a mean velocity of 0.63 m/s at a site where American shad eggs were collected in the lower Roanoke River. In a review by Bilkovic et al. (2002), 0.3 to 0.7 was suggested as an optimal range of current velocities for egg and larval development. I found the mean current velocities for the months of March through June to be between 0.27 and 0.58 m/s, or within these recommended ranges for spawning and nursery habitat for American shad. The lowest value for current velocity was found on the Staunton River immediately below Leesville Dam, during periods of little to no discharge. The highest values for current velocity were found on the Big Otter and Dan rivers. These values are highly variable depending on recent local rainfall as well as dam discharge schedules.

Conductivity

Conductivity is a measure of dissolved ions in the water and the ability of water to pass an electrical current (Bain 1999). Under normal conditions, conductivity is primarily affected by the geology of the area through which water flows (Bain 1999). Areas high in clay soils tend to have higher conductivities (Bain 1999), which may contribute to the relatively high conductivity values found within the Roanoke River basin. Conductivity is not mentioned in the literature as an important parameter for American shad spawning and nursery habitat, but I chose to measure it because it can be used as an indicator for upstream pollution in rivers (Bain 1999). Discharges to streams can change the conductivity; for example, a faulty sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate ions (U.S. Environmental Protection Agency 2001). Specific conductance measured on the five rivers ranged between 97 and 116 μS. Conductivity did not change substantially over seasons and the lowest values were consistently found on the Banister and Big Otter rivers.

Turbidity

Turbidity is a measure of the degree to which light penetration is reduced by suspended solids (Armantrout 1998). Total suspended solids (TSS) concentration and turbidity both indicate the amount of suspended matter in the water; however, TSS measures the actual amount of material per volume of water while turbidity measures the amount of light scattered from a sample (Metro 1990). Sources of turbidity include soil erosion, waste discharge, urban runoff, eroding streambanks, large numbers of bottom feeders, and excessive algal growth (EPA Monitoring and Assessing Water Quality Database). Stier and Crance (1985) suggested that suspended sediments should not exceed 100 ppm (100 mg/L) on American shad spawning grounds. This contradicts research by Auld and Schubel (1978) who found that prolonged exposures of eggs to suspended sediments of up to 1,000 mg/L had no negative effects on egg development. They did find, however, that larvae were more sensitive to prolonged exposures to high suspended sediment concentrations. Ross et al. (1993a) observed spawning at low turbidities and suggested that optimum spawning conditions in the Delaware River occurred at very low turbidities (less than 2.7 ntu). On the other hand, Walburg and Nichols (1967) suggested that American shad could spawn and thrive in waters that are “clear to very turbid.” Chittenden (1976) reported that time of spawning is controlled by light intensity. He noted that spawning tends to occur at nightfall; therefore, higher water turbidities that effect light intensity could regulate the daily onset of spawning and allow for spawning to occur during daytime rather than just at nightfall. It has also been proposed that American shad have the ability to live or pass through very turbid waters which may serve as a defense mechanism against potential predators or provide selective advantage over other species that may not be able to tolerate wide ranges of turbidity (Leim 1924; Massmann 1952; Dadswell et al. 1983).

I found a wide range of turbidities with mean values ranging between 9.6 and 95.2 ntu. Turbidities were generally lower in the drier months between October and February, but starting in April turbidities increased and continued to rise throughout the summer months. There were particularly high turbidity levels (above 300 ntu) in April because of a very heavy rainfall on the day of data collection. Egg incubation experiments on these same rivers (Chapter 2) suggest that high turbidity levels ranging up to 62.6 ntu did not have significant effects on hatching success of American shad eggs suspended in incubators. Further study is necessary to evaluate egg hatching results for eggs incubated in contact with the substrate.

pH

The pH is a measure of hydrogen ion activity in the water (Bain 1999). Bilkovic et al. (2002) used results of bio-assay experiments (Bradford et al. 1968) to establish a range of 6.0 to 9.9 as optimal for American shad spawning adults and egg and larval development. Our circuit sampling produced only one value below 6.0, on the Big Otter River (State Route 682 near Evington) where the pH measured 5.8.

Substrate Composition

American shad have been observed to spawn over a variety of substrates including silt, sand, muck, gravel, and boulder (Mansueti and Kolb 1953) but most frequently over sand or gravel or a combination of both (Walburg and Nichols 1967). Stier and Crance (1985) did not include bottom substrate as an essential parameter for identifying spawning and nursery habitat because it has been widely cited that American shad have been observed to spawn over all types of substrates (Hildebrand and Schroeder 1928; Massmann 1952; Marcy 1972). Bilkovic et al. (2002) defined sand and gravel substrates as optimal, and assumed that mud and silt substrates had a suitability of 0. Perhaps the most substantial evidence of a preferred substrate for spawning American shad comes from two studies in the Neuse River where spawning activity was observed (Beasley and Hightower 2000; Bowman and Hightower 2001). Both studies found that spawning activity occurred at higher frequencies over larger substrates (gravel, cobble, and boulder), even when a greater amount of sandy substrates were available. A wide variety of substrates were found in the Roanoke River basin above Kerr Lake; each river had a different proportion of the various substrates. Larger substrates, like those found in the Neuse River studies (Beasley and Hightower 2000; Bowman and Hightower 2001) were found primarily along the upper Staunton and Big Otter rivers, but some larger substrates were also found in the Banister River.

Percent Overhang and Occurrence of Woody Debris

Data on percent overhang and woody debris presence were collected because it has been observed that many species of fish prefer cover for refuge that overhanging vegetation and woody debris can provide (Stevenson and Bain 1999). There are no suitability curves available for American shad, but it was suggested by Delphi panelists in the Stier and Crance (1984) study that spawning adults may use various types of cover for resting areas during upstream migration. Because light intensity influences timing of spawning, decreased light due to greater overhang could influence time of day of spawning activity (Whitney 1961). In general, the three smaller rivers (Big Otter, Banister, and Hyco) had higher percentages of shade provided by overhanging vegetation, and higher amounts of visible woody debris present. The larger Dan and Staunton rivers had over 98% of the river classified as 1-25% overhang and also little presence of visible woody debris.

Longitudinal Classification

Riffles were encountered quite frequently on the upper Staunton and Big Otter rivers. The majority of the remainder of the habitat was classified as run habitat. Riffle habitats typically contain areas with considerable turbulence and higher velocities. These areas also characteristically contain larger substrates. Chittenden (1976) reported that American shad spawning activity was concentrated in shallow riffle areas in the Delaware River. Conversely, Ross et al. (1993a), also in the Delaware River, observed spawning in all longitudinal classifications but most often in runs and least often in pools and riffle pools. Bilkovic et al. (2002) suggested that upstream reaches may be optimal for spawning because of the shallow water, high dissolved oxygen, and fast currents that could help in preventing siltation or suffocation of eggs, and favor transport of eggs and larvae. These studies (Bilkovic et al 2002; Ross et al. 1993b) suggested that riffle areas, defined as a “zone of shallow swift water with surface turbulence or aeration,” may be characteristic of suitable spawning habitat.

Habitat Suitability Index Models

The addition of a model sub-component for substrate appears to be useful for determining suitable areas for spawning. The original Steir and Crance (1985) model (Model 1) is effectively temperature driven because current velocities are typically within the optimal range. Model 2 is very similar to model 1 in that it is largely temperature driven, regardless of the addition of the IFIM substrate values. This is because the IFIM suitability curve ranks sand, which occurs at many sites, as highly suitable. Model 2 uses a wider temperature range than Model 1 so HSI values tend to be somewhat higher. Model 3 is largely substrate driven because of the relatively wide optimal temperature range and the low assumed suitability of sand substrate. This model appears to be the most conservative for discriminating among areas, assuming that the preferences observed in the Neuse River would apply here.

Summary

The five rivers of the Roanoke basin above Kerr Lake contain over 300 rkm of potentially suitable spawning and nursery habitat for American shad. The potential value depends on which variables are assumed to be important in defining optimal spawning habitat. The rivers differ in the amount of sand versus larger substrates and in the amount of shallow riffle areas versus run habitat. Water quality was generally good during spring and similar among rivers except for lower conductivities in the Big Otter and Banister rivers. HSI values from Model 3 indicated the best potential spawning habitat may be located on the Big Otter and Staunton rivers. The Dan, Hyco and Banister rivers are ranked lower because the substrate was sand or silt at most sites. These predictions about habitat quality could be refined through further studies regarding spawning activity versus substrate, including egg incubation experiments that address substrate type. Also, once adult American shad are stocked into these areas, telemetry methods or egg and larval sampling could be done to determine the relative use of river reaches containing different habitats.

Table 1. Primary sources reviewed to determine suitable ranges for variables important for American shad spawning and nursery habitat.

Variable	Range or Description	Reference	Life Stage Specified
Bottom Substrate	Observed spawning primarily over gravel or bedrock substrate	Beasley and Hightower 2000	spawning adults
Bottom Substrate	Category >/=2 (1=mud/silt, 2=sand, 3=gravel)	Bilkovik et al. 2002	eggs and larvae
Bottom Substrate	"coarse substrates consisting of gravel, cobble and boulder"	Bowman and Hightower 2001	spawning adults
Bottom Substrate	"Larger substrates observed on spawning grounds consisting of 48% gravel, 16% cobble, 15% bedrock, and 15% sand"	Hightower and Sparks 2003	spawning adults
Bottom Substrate	"spawn over sand, silt, muck, gravel, and boulder"	Mansueti and Kolb 1953	spawning adults
Bottom Substrate	"preferably over sand and gravel bottom"	Stier and Crance 1985	spawning adults
Bottom Substrate	"spawning occurs over various substrate types but most abundantly over sand, gravel or a combination of both"	Walburg and Nichols 1967	juveniles/spawning adults
Current Velocity	Range of 0.06-1.28 m/sec	Beasley and Hightower 2000	spawning adults
Current Velocity	0.3-0.7m/s, optimal	Bilkovik et al. 2002	eggs and larvae
Current Velocity	0.2-0.6 m/sec	Bowman and Hightower 2001	spawning adults
Current Velocity	0.63 m/s mean	Hightower and Sparks 2003	spawning adults
Current Velocity	0-0.91m/s	Massmann 1952	spawning adults
Current Velocity	0.3-0.9 m/s, 0.0-0.7 m/s observed	Ross et al. 1993b	spawning adults
Current Velocity	eggs and larvae were found at all velocities less than 1m/s	Ross et al. 1993b	eggs and larvae
Current Velocity	0.09-1.32 m/s; "sufficient current velocities to to eliminate silt deposits"	Stier and Crance 1985	spawning adults
Current Velocity	0.305-0.914 m/s	Walburg and Nichols 1967	spawning adults
Depth	0.3-1.83 m	Beasley and Hightower 2000	spawning adults
Depth	1.5-6.1 m, optimal	Bilkovik et al. 2002	eggs and larvae
Depth	0.5-1.25 m	Bowman and Hightower 2001	spawning adults
Depth	2.5 m mean depth	Hightower and Sparks 2003	spawning adults
Depth	"observed at all depths in rivers, specifically 0.45 to 12.2 m"	Stier and Crance 1985	spawning adults
Depth	0.9-9.1 m, can be up to 12.2 m	Walburg and Nichols 1967	spawning adults
Dissolved Oxygen	>5 mg/L	Bilkovik et al. 2002	spawning adults/eggs and larvae
Dissolved Oxygen	>5 mg/L	Marcy 1972	eggs
Dissolved Oxygen	>5 mg/L	Ross et al. 1993b	spawning adults/eggs and larvae
Dissolved Oxygen	>5 mg/L	Stier and Crance 1985	spawning adults/eggs and larvae
Dissolved Oxygen	>5 mg/L	Walburg and Nichols 1967	spawning adults
pH	6.0-9.9	Bilkovik et al. 2002	spawning adults/eggs and larvae
Temperature	Observed spawning activity between 18-23.7°C	Beasley and Hightower 2000	spawning adults
Temperature	14.5-24.5°C, optimal; <8°C and >27°C unsuitable	Bilkovik et al. 2002	spawning adults/eggs and larvae
Temperature	"optimum survival of shad eggs occurred at ~17°C", hatching and survival are at a max between 15.5 and 26.5°C	Leggett 1973	eggs and larvae
Temperature	peak spawning between 14.8 and 22°C	Marcy 1972	spawning adults
Temperature	median spawning temperature is between 16 and 17°C	Massmann 1952	spawning adults
Temperature	14-24.5°C (extended the upper maximum limit from Stier and Crance (1985))	Ross et al. 1993b	spawning adults
Temperature	15-26.5°C (extension of upper thermal limit from Stier and Crance (1985))	Ross et al. 1993b	eggs and larvae
Temperature	14-20°C	Stier and Crance 1985	spawning adults
Temperature	15-25°C	Stier and Crance 1985	eggs and larvae
Temperature	8-26(°C), 14-21(°C) usually	Walburg and Nichols 1967	spawning adults
Turbidity	Reports that eggs are not significantly effected by prolonged exposure to suspended sediment concentrations of up to 1000 mg/L, but larvae are less tolerant to prolonged exposure.	Auld and Schubel 1978	eggs and larvae
Turbidity	>/= 0.3 m (secchi depth)	Bilkovik et al. 2002	spawning adults/eggs and larvae
Turbidity	Notes that high turbidities may influence daily onset of spawning, can cause spawning to occur all day long (instead of just at night), no mention of negative effects of high turbidities.	Chittenden 1976	spawning adults
Turbidity	"water was extremely turbid", " the muddy waters seemed to be in no way injurious to shad" and possibly serves as a protectant against predators	Leim 1924	juveniles
Turbidity	reports that shad pass through maximum turbidity waters	Massmann 1952	spawning adults
Turbidity	eggs not found above 2.7 ntu, larvae not found above 2.1 ntu	Ross et al. 1993b	eggs and larvae
Turbidity	greater than 100 ppm is unsuitable for larval development	Stier and Crance 1985	larvae
Turbidity	"clear to very turbid"	Walburg and Nichols 1967	spawning adults

Table 2. Longitudinal Classification scheme used in characterizing Roanoke River basin as defined by Ross et al. (1993b) and Kynard et al. (2000)

Longitudinal Classification	Definition	Reference
Run	A midwater stretch of relatively shallow (0.5-1.5 m) water with moderate to high current velocity (0.3-0.7 m/s)	Ross et al. 1993b
Run with Island	Run with island 150 m up- and downstream	Kynard et al. 2000
Riffle	A zone of shallow (less than or equal to 0.5 m) swift (>0.5 m/s) water with surface turbulence/aeration	Ross et al. 1993b
Riffle Pool	Zone immediately following a riffle where water deepens suddenly and currents become variable in velocity and direction	Ross et al. 1993b
Pool	A relatively large river segment where the river widens, depth increases, and current velocities drop (<o.25 m/s), typically just upstream of a series of riffles	Ross et al. 1993b

Table 3. Modified Wentworth (1922) particle scale ranking system (Schaffter 1997) for particle size identification and substrate classification.

Particle Category	**Size class (mm)**	**rank**
Silt/Clay	<0.62	1
Sand	0.62-2.0	2
Fine Gravel	2.0-16.0	3
Coarse Gravel	16.0-64.0	4
Cobble	64.0-250.0	5
Boulder	250.0-4,000.0	6
Bedrock	>4,000.0	7

Table 4. Means, standard errors, and ranges taken from physical habitat assessment data collected during the summer of 2003

River	Month		DO (mg/L)	Temperature (°C)	pH	Turbidity (ntu)	Current Velocity (m/s)	Conductivity (µS)	Width (m)*	Depth (m)*
Big Otter	October	Mean	11.57	11.50	7.50	5.20	0.40	70.04	19.71	0.66
		SE	0.13	0.13	0.05	1.08	0.08	5.09	2.71	0.14
		Range	10.85 - 11.86	11.00 -12.00	7.34 - 7.70	2.5 - 10.2	0.17 - 0.62	54.7 - 89.7	9.0 - 31.0	0.3 - 1.3
Staunton	July	Mean	6.48	23.11	7.60	20.31	0.78	167.22	76.83	1.63
		SE	0.12	0.27	0.04	15.17	0.04	1.79	2.03	0.09
		Range	5.33 - 7.89	21.4 - 25.2	7.00 - 8.61	5.8 - 48.6	0.16 - 2.02	147.5 - 188.8	55.0 - 119.0	0.3 - 4.8
	October	Mean	9.61	17.88	7.25	5.92	0.47	134.48	76.83	1.63
		SE	0.22	0.46	0.05	25.42	0.05	2.47	2.03	0.09
		Range	7.99 - 11.49	15.6 - 19.7	7.00 - 7.60	3.1 - 12.5	0.04 - 1.15	131.9 - 138.6	31.0 - 124.0	0.7 - 2.2
Banister	October	Mean	7.14	16.63	7.03	37.25	0.22	72.18	30.75	0.83
		SE	0.09	0.15	0.05	1.00	0.03	0.59	1.70	0.13
		Range	6.86 - 7.26	16.20 - 16.90	6.95 - 7.15	35.5 - 40.1	0.14 - 0.27	70.50 - 73.10	26.0 - 34.0	0.5 - 1.1
Dan	July	Mean	6.64	24.10	7.25	232.54	0.96	83.64	72.02	2.49
		SE	0.14	0.21	0.02	23.13	0.04	2.14	1.51	0.12
		Range	4.74 - 9.46	21.30 - 26.50	7.04 - 7.83	41.5 - 611.0	0.37 - 1.62	56.2 - 111.3	43.0 - 131.0	1.0 - 4.3
Hyco	July	Mean	4.08	27.26	6.38	18.82	0.09	107.36	59.40	4.00
		SE	0.30	0.45	0.05	49.08	0.10	4.71	7.18	0.27
		Range	3.37 - 4.89	26.90 - 27.80	6.00 - 6.80	17.1 - 20.9	0.03 - 0.24	102.2 - 110.4	22.0 - 296.0	1.2 - 6.8
	October	Mean	6.87	18.01	7.03	6.67	0.14	100.97	25.50	1.42
		SE	0.34	0.51	0.06	55.61	0.11	5.35	7.18	0.27
		Range	6.47 - 7.44	17.7 - 18.5	6.5 - 7.4	5.2 - 7.8	0.03 - 0.49	96.8 - 108.8	17.0 - 35.0	0.8 - 2.1

* all sample points for individual rivers are included in these values

Table 5. Suitability values for surface water temperature during spawning season, as defined by Stier and Crance (1985), using historical data from USGS and VADEQ water quality monitoring stations. Sample size for measurements shown in parenthesis.

River	Site	Average values for Temperature (°C)				SI for Temperature			
		March	April	May	June	March	April	May	June
Big Otter	Evington, VA	9.4 (15)	14.0 (10)	18.9 (11)	23.2 (11)	0.23	1.00	1.00	0.46
Staunton	Altavista, VA	7.5 (10)	14.1 (10)	16.1 (10)	19.4 (9)	0.00	1.00	1.00	1.00
	Brookneal, VA	10.6 (15)	15.6 (13)	19.3 (16)	23.9 (13)	0.44	1.00	1.00	0.36
	Randolph, VA	8.1 (14)	14.2 (16)	17.8 (13)	23.3 (13)	0.01	1.00	1.00	0.45
Banister	Halifax, VA	9.0 (14)	15.2 (17)	19.2 (15)	23.0 (16)	0.16	1.00	1.00	0.50
Dan	Danville, VA	10.3 (10)	15.8 (11)	20.3 (10)	23.8 (10)	0.39	1.00	0.95	0.36
	Paces, VA	9.3 (5)	15.2 (9)	18.7 (5)	24.6 (5)	0.22	1.00	1.00	0.24
Hyco	Denniston, VA	9.4 (5)	15.5 (6)	20.8 (5)	23.7 (5)	0.24	1.00	0.87	0.38
Roanoke	Roanoke Rapids, NC	6.6 (5)	14.1 (12)	18.7 (18)	23.2 (5)	0.00	1.00	1.00	0.47

Table 6. Suitability values for surface water current velocity during spawning season, as defined by Stier and Crance (1985), using historical data from USGS and VADEQ water quality monitoring stations. Sample size for measurements shown in parenthesis.

River	Site	Average values for Current Velocity (m/s)				SI for Current Velocity			
		March	April	May	June	March	April	May	June
Big Otter	Evington, VA	0.66 (52)	0.64 (45)	0.61 (43)	0.52 (45)	1.00	1.00	1.00	1.00
Staunton	Altavista, VA	0.67 (9)	0.56 (2)	0.64 (12)	0.53 (9)	1.00	1.00	1.00	1.00
	Brookneal, VA	0.84 (11)	0.86 (9)	0.87 (9)	0.68 (11)	1.00	1.00	1.00	1.00
	Randolph, VA	0.70 (9)	0.70 (8)	0.76 (11)	0.65 (10)	1.00	1.00	1.00	1.00
Banister	Halifax, VA	0.52 (4)	0.40 (4)	0.36 (2)	0.29 (8)	1.00	1.00	1.00	0.95
Dan	Danville, VA	0.84 (10)	0.80 (6)	0.79 (5)	0.67 (8)	1.00	1.00	1.00	1.00
	Paces, VA	0.71 (14)	0.78 (11)	0.66 (10)	0.61 (10)	1.00	1.00	1.00	1.00
Hyco	Denniston, VA	0.38 (14)	0.36 (14)	0.27 (8)	0.24 (12)	1.00	1.00	0.83	0.71
Roanoke	Roanoke Rapids, NC	0.73 (24)	0.78 (35)	0.59 (34)	0.64 (14)	1.00	1.00	1.00	1.00

Table 7. Suitability values for surface water temperature during egg and larval development, as defined by Stier and Crance (1985), using historical data from USGS and VADEQ water quality monitoring stations. Sample size for measurements shown in parenthesis.

River	Site	Average values for Temperature (°C)				SI for Temperature			
		March	April	May	June	March	April	May	June
Big Otter	Evington, VA	9.4 (15)	14.0 (10)	18.9 (11)	23.2 (11)	0.00	0.79	1.00	1.00
Staunton	Altavista, VA	7.5 (10)	14.1 (10)	16.1 (10)	19.4 (9)	0.00	0.82	1.00	1.00
	Brookneal, VA	10.6 (15)	15.6 (13)	19.3 (16)	23.9 (13)	0.13	1.00	1.00	1.00
	Randolph, VA	8.1 (14)	14.2 (16)	17.8 (13)	23.3 (13)	0.00	0.84	1.00	1.00
Banister	Halifax, VA	9.0 (14)	15.2 (17)	19.2 (15)	23.0 (16)	0.00	1.00	1.00	1.00
Dan	Danville, VA	10.3 (10)	15.8 (11)	20.3 (10)	23.8 (10)	0.06	1.00	1.00	1.00
	Paces, VA	9.3 (5)	15.2 (9)	18.7 (5)	24.6 (5)	0.00	1.00	1.00	1.00
Hyco	Denniston, VA	9.4 (5)	15.5 (6)	20.8 (5)	23.7 (5)	0.00	1.00	1.00	1.00
Roanoke	Roanoke Rapids, NC	6.6 (5)	14.1 (12)	18.7 (18)	23.2 (5)	0.00	0.82	1.00	1.00

Table 8. Overall Riverine Habitat Suitability Index (HSI) values, as defined by Stier and Crance (1985), using historical data from USGS and VADEQ water quality monitoring stations

River	Site	Riverine HSI			
		March	April	May	June
Big Otter	**Evington, VA**	0.00	0.79	1.00	0.46
Staunton	**Altavista, VA**	0.00	0.82	1.00	1.00
	Brookneal, VA	0.13	1.00	1.00	0.36
	Randolph, VA	0.00	0.84	1.00	0.45
Banister	**Halifax, VA**	0.00	1.00	1.00	0.50
Dan	**Danville, VA**	0.06	1.00	0.95	0.36
	Paces, VA	0.00	1.00	1.00	0.24
Hyco	**Denniston, VA**	0.00	1.00	0.83	0.38
Roanoke	**Roanoke Rapids, NC**	0.00	0.82	1.00	0.47

Table 9. Total number of suitable river kilometers (rkm) for each river using the three Habitat Suitability Index Models, using an HSI value of 0.60 as a cut-off for suitable habitat (circuit sampling data from 2004 was used).

River	Model 1				Model 2				Model 3			
	March	April	May	June	March	April	May	June	March	April	May	June
Big Otter	0	0	29	21	0	0	29	29	0	0	29	29
Staunton	0	0	74	23	0	0	103	103	0	0	23	0
Banister	0	0	0	0	0	0	8	8	0	0	0	10
Dan	0	0	0	13	13	0	44	79	0	0	10	0
Hyco	0	6	0	0	6	6	6	0	0	0	0	0
Total (rkm)	**0**	**6**	**103**	**57**	**19**	**6**	**190**	**219**	**0**	**0**	**62**	**39**

Table 10. Suitability values for surface water temperature during spawning season (Model 1), as defined by Stier and Crance (1985), using circuit sampling data from 2004.

River	Site	Values for Temperature (°C)				SI for Temperature			
		Mar-04	Apr-04	May-04	Jun-04	Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	4.8	9.1	19.6	19.6	0.00	0.18	1.00	1.00
	2	4.9	9.3	20.3	20.2	0.00	0.22	0.95	0.97
	3	5.5	9.3	21.1	20.9	0.00	0.22	0.82	0.85
	4	6.9	9.3	22.2	22.6	0.00	0.22	0.63	0.57
Staunton	5	10.3	10.4	17.0	20.9	0.38	0.40	1.00	0.85
	6	8.4	9.9	17.9	21.3	0.07	0.32	1.00	0.78
	7	8.4	9.7	20.5	22.3	0.07	0.28	0.92	0.62
	8	8.6	9.7	21.5	22.9	0.10	0.28	0.75	0.52
	9	9.5	10.1	22.9	22.5	0.25	0.35	0.52	0.58
	10	9.6	10.5	22.9	22.6	0.27	0.42	0.52	0.57
Dan	11	12.3	11.8	26.1	22.2	0.72	0.63	0.00	0.63
	12	11.6	11.3	25.5	22.6	0.60	0.55	0.08	0.57
	13	11.3	11.2	25.4	22.7	0.55	0.53	0.10	0.55
	14	11.4	11.4	25.5	23.1	0.57	0.57	0.08	0.48
	15	11.5	11.4	25.6	23.2	0.58	0.57	0.07	0.47
Banister	16	11.2	11.3	24.0	23.3	0.53	0.55	0.33	0.45
	17	11.5	11.4	23.8	22.9	0.58	0.57	0.37	0.52
	18	11.1	11.7	23.5	22.9	0.52	0.62	0.42	0.52
	19	10.8	11.8	23.3	23.3	0.47	0.63	0.45	0.45
Hyco	20	11.9	12.0	25.1	26.2	0.65	0.67	0.15	0.00
	21	10.3	11.2	22.7	25.3	0.38	0.53	0.55	0.12
	22	7.3	11.4	22.8	24.2	0.00	0.57	0.53	0.30
	23	11.9	13.6	23.0	24.7	0.65	0.93	0.50	0.22

Table 11. Suitability values for current velocity during spawning season (Model 1), as defined by Stier and Crance (1985), using circuit sampling data from 2004.

River	Site	Values for Current Velocity (m/s)				SI for Current Velocity			
		Mar-04	Apr-04	May-04	Jun-04	Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	0.55	0.71	0.52	0.30	1.00	1.00	1.00	0.99
	2	0.62	0.33	0.51	0.29	1.00	1.00	1.00	0.94
	3	0.27	0.40	0.14	0.19	0.84	1.00	0.25	0.48
	4	0.35	0.83	0.59	0.29	1.00	1.00	1.00	0.94
Staunton	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	0.34	0.58	0.43	0.24	1.00	1.00	1.00	0.70
	7	0.21	0.38	0.29	0.21	0.56	1.00	0.94	0.54
	8	0.53	0.68	0.47	0.48	1.00	1.00	1.00	1.00
	9	0.56	0.56	0.57	0.42	1.00	1.00	1.00	1.00
	10	0.24	0.53	0.37	0.32	0.70	1.00	1.00	1.00
Dan	11	0.35	0.54	0.68	0.42	1.00	1.00	1.00	1.00
	12	0.56	0.53	0.68	0.44	1.00	1.00	1.00	1.00
	13	0.36	0.43	0.42	0.34	1.00	1.00	1.00	1.00
	14	0.37	0.55	0.59	0.35	1.00	1.00	1.00	1.00
	15	0.52	0.51	0.59	0.32	1.00	1.00	1.00	1.00
Banister	16	0.30	0.48	0.45	0.34	0.98	1.00	1.00	1.00
	17	0.46	0.51	0.63	0.38	1.00	1.00	1.00	1.00
	18	0.25	0.65	0.42	0.41	0.74	1.00	1.00	1.00
	19	0.44	0.52	0.63	0.28	1.00	1.00	1.00	0.86
Hyco	20	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
	21	0.26	0.45	0.21	0.11	0.79	1.00	0.56	0.09
	22	0.42	0.46	0.50	0.48	1.00	1.00	1.00	1.00
	23	0.32	0.75	0.43	0.14	1.00	1.00	1.00	0.23

Table 12. Suitability values for surface water temperature during egg and larval development (Model 1), as defined by Stier and Crance (1985), using circuit sampling data from 2004.

River	Site	Values for Temperature (°C)				SI for Temperature			
		Mar-04	Apr-04	May-04	Jun-04	Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	4.8	9.1	19.6	19.6	0.00	0.00	1.00	1.00
	2	4.9	9.3	20.3	20.2	0.00	0.00	1.00	1.00
	3	5.5	9.3	21.1	20.9	0.00	0.00	1.00	1.00
	4	6.9	9.3	22.2	22.6	0.00	0.00	1.00	1.00
Staunton	5	10.3	10.4	17.0	20.9	0.06	0.08	1.00	1.00
	6	8.4	9.9	17.9	21.3	0.00	0.00	1.00	1.00
	7	8.4	9.7	20.5	22.3	0.00	0.00	1.00	1.00
	8	8.6	9.7	21.5	22.9	0.00	0.00	1.00	1.00
	9	9.5	10.1	22.9	22.5	0.00	0.02	1.00	1.00
	10	9.6	10.5	22.9	22.6	0.00	0.10	1.00	1.00
Dan	11	12.3	11.8	26.1	22.2	0.46	0.36	0.78	1.00
	12	11.6	11.3	25.5	22.6	0.32	0.26	0.90	1.00
	13	11.3	11.2	25.4	22.7	0.26	0.24	0.92	1.00
	14	11.4	11.4	25.5	23.1	0.28	0.28	0.90	1.00
	15	11.5	11.4	25.6	23.2	0.30	0.28	0.88	1.00
Banister	16	11.2	11.3	24.0	23.3	0.24	0.26	1.00	1.00
	17	11.5	11.4	23.8	22.9	0.30	0.28	1.00	1.00
	18	11.1	11.7	23.5	22.9	0.22	0.34	1.00	1.00
	19	10.8	11.8	23.3	23.3	0.16	0.36	1.00	1.00
Hyco	20	11.9	12.0	25.1	26.2	0.38	0.40	0.98	0.76
	21	10.3	11.2	22.7	25.3	0.06	0.24	1.00	0.94
	22	7.3	11.4	22.8	24.2	0.00	0.28	1.00	1.00
	23	11.9	13.6	23.0	24.7	0.38	0.72	1.00	1.00

Table 13. Overall Riverine Habitat Suitability Index (HSI) values (Model 1), as defined by Stier and Crance (1985), using circuit sampling data from 2004.

River	Site	Model 1 Riverine HSI			
		Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	0.00	0.00	1.00	0.99
	2	0.00	0.00	0.95	0.94
	3	0.00	0.00	0.25	0.48
	4	0.00	0.00	0.63	0.57
Staunton	5	0.00	0.00	0.00	0.00
	6	0.00	0.00	1.00	0.70
	7	0.00	0.00	0.92	0.54
	8	0.00	0.00	0.75	0.52
	9	0.00	0.02	0.52	0.58
	10	0.00	0.10	0.52	0.57
Dan	11	0.46	0.36	0.00	0.63
	12	0.32	0.26	0.08	0.57
	13	0.26	0.24	0.10	0.55
	14	0.28	0.28	0.08	0.48
	15	0.30	0.28	0.07	0.47
Banister	16	0.24	0.26	0.33	0.45
	17	0.30	0.28	0.37	0.52
	18	0.22	0.34	0.42	0.52
	19	0.16	0.36	0.45	0.45
Hyco	20	0.00	0.00	0.00	0.00
	21	0.06	0.24	0.55	0.09
	22	0.00	0.28	0.53	0.30
	23	0.38	0.72	0.50	0.22

Table 14. Water temperatures from March-June 2004 circuit sampling and suitability index values, based on modified suitability curve used in HSI Models 2-3.

River	Site	Values for Temperature (°C)				Model 2 and 3 SI for Temperature			
		Mar-04	Apr-04	May-04	Jun-04	Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	4.8	9.1	19.6	19.6	0.00	0.17	1.00	1.00
	2	4.9	9.3	20.3	20.2	0.00	0.20	1.00	1.00
	3	5.5	9.3	21.1	20.9	0.00	0.20	1.00	1.00
	4	6.9	9.3	22.2	22.6	0.00	0.20	1.00	1.00
Staunton	5	10.3	10.4	17.0	20.9	0.35	0.37	1.00	1.00
	6	8.4	9.9	17.9	21.3	0.06	0.29	1.00	1.00
	7	8.4	9.7	20.5	22.3	0.06	0.26	1.00	1.00
	8	8.6	9.7	21.5	22.9	0.09	0.26	1.00	1.00
	9	9.5	10.1	22.9	22.5	0.23	0.32	1.00	1.00
	10	9.6	10.5	22.9	22.6	0.25	0.39	1.00	1.00
Dan	11	12.3	11.8	26.1	22.2	0.66	0.59	0.36	1.00
	12	11.6	11.3	25.5	22.6	0.55	0.51	0.60	1.00
	13	11.3	11.2	25.4	22.7	0.51	0.49	0.64	1.00
	14	11.4	11.4	25.5	23.1	0.52	0.52	0.60	1.00
	15	11.5	11.4	25.6	23.2	0.54	0.52	0.56	1.00
Banister	16	11.2	11.3	24.0	23.3	0.49	0.51	1.00	1.00
	17	11.5	11.4	23.8	22.9	0.54	0.52	1.00	1.00
	18	11.1	11.7	23.5	22.9	0.48	0.57	1.00	1.00
	19	10.8	11.8	23.3	23.3	0.43	0.59	1.00	1.00
Hyco	20	11.9	12.0	25.1	26.2	0.60	0.62	0.76	0.32
	21	10.3	11.2	22.7	25.3	0.35	0.49	1.00	0.68
	22	7.3	11.4	22.8	24.2	0.00	0.52	1.00	1.00
	23	11.9	13.6	23.0	24.7	0.60	0.86	1.00	0.92

Table 15. Suitability values for bottom substrate (Model 2) for both spawning season and egg and larval development, using data from 2003. Bottom substrate values are defined using the modified Wentworth (1922) particle scale ranking system: 1=silt/clay, 2=sand, 3=gravel, 4=cobble, 5=boulder, 6=bedrock. Suitability curve based on IFIM data (Stier and Crance 1985)

River	Site	Bottom Substrate	SI
Big Otter	1	4.6	1.00
	2	4.5	1.00
	3	4.5	1.00
	4	4.0	1.00
Staunton	5	3.9	1.00
	6	3.3	1.00
	7	5.0	0.60
	8	3.1	1.00
	9	2.2	1.00
	10	2.1	1.00
Dan	11	2.4	1.00
	12	2.3	1.00
	13	2.1	1.00
	14	2.2	1.00
	15	2.1	1.00
Banister	16	2.5	1.00
	17	6.0	0.40
	18	4.0	1.00
	19	1.5	0.20
Hyco	20	2.1	1.00
	21	3.2	1.00
	22	1.8	0.20
	23	2.5	1.00

Table 16. Overall Model 2 Riverine Habitat Suitability Index (HSI) values calculated with the current velocity range defined by Stier and Crance (1985), a revised temperature range (Bilkovik et al. 2002; Ross et al. 1993), and the IFIM substrate curve (Stier and Crance 1985) using data collected during 2003 and 2004.

River	Site	Model 2 Riverine HSI			
		Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	0.00	0.17	1.00	0.99
	2	0.00	0.20	1.00	0.94
	3	0.00	0.20	0.25	0.48
	4	0.00	0.20	1.00	0.94
Staunton	5	0.00	0.00	0.00	0.00
	6	0.06	0.29	1.00	0.70
	7	0.06	0.26	0.60	0.54
	8	0.09	0.26	1.00	1.00
	9	0.23	0.32	1.00	1.00
	10	0.25	0.39	1.00	1.00
Dan	11	0.66	0.59	0.36	1.00
	12	0.55	0.51	0.60	1.00
	13	0.51	0.49	0.64	1.00
	14	0.52	0.52	0.60	1.00
	15	0.54	0.52	0.56	1.00
Banister	16	0.49	0.51	1.00	1.00
	17	0.40	0.40	0.40	0.40
	18	0.48	0.57	1.00	1.00
	19	0.20	0.20	0.20	0.20
Hyco	20	0.00	0.00	0.00	0.00
	21	0.35	0.49	0.56	0.09
	22	0.00	0.20	0.20	0.20
	23	0.60	0.86	1.00	0.23

Table 17. Suitability values for bottom substrate (Model 3) for American shad spawning, using data from 2003. Bottom substrate values are defined using the modified Wentworth (1922) particle scale ranking system: 1=silt/clay, 2=sand, 3=gravel, 4=cobble, 5=boulder, 6=bedrock. The suitability curve is based on research results from the Neuse River (Beasley and Hightower 2000; Bowman and Hightower 2001).

River	Site	Bottom Substrate	SI
Big Otter	1	4.6	0.80
	2	4.5	0.80
	3	4.5	0.80
	4	4.0	0.80
Staunton	5	3.9	0.40
	6	3.3	0.40
	7	5.0	1.00
	8	3.1	0.40
	9	2.2	0.20
	10	2.1	0.20
Dan	11	2.4	0.20
	12	2.3	0.20
	13	2.1	0.20
	14	2.2	0.20
	15	2.1	0.20
Banister	16	2.5	0.20
	17	6.0	1.00
	18	4.0	0.80
	19	1.5	0.20
Hyco	20	2.1	0.20
	21	3.2	0.40
	22	1.8	0.20
	23	2.5	0.20

Table 18. Overall Riverine Habitat Suitability Index (HSI) values (Model 3) calculated with the current velocity range defined by Stier and Crance (1985), a revised temperature range (Bilkovik et al. 2002; Ross et al. 1993), and a component for bottom substrate (Beasley and Hightower 2000; Bowman and Hightower 2001) using data collected during 2003 and 2004.

River	Site	Model 3 Riverine HSI			
		Mar-04	Apr-04	May-04	Jun-04
Big Otter	1	0.00	0.17	0.80	0.80
	2	0.00	0.20	0.80	0.80
	3	0.00	0.20	0.25	0.48
	4	0.00	0.20	0.80	0.80
Staunton	5	0.00	0.00	0.00	0.00
	6	0.06	0.29	0.40	0.40
	7	0.06	0.26	0.94	0.54
	8	0.09	0.26	0.40	0.40
	9	0.20	0.20	0.20	0.20
	10	0.20	0.20	0.20	0.20
Dan	11	0.20	0.20	0.20	0.20
	12	0.20	0.20	0.20	0.20
	13	0.20	0.20	0.20	0.20
	14	0.20	0.20	0.20	0.20
	15	0.20	0.20	0.20	0.20
Banister	16	0.20	0.20	0.20	0.20
	17	0.54	0.52	1.00	1.00
	18	0.48	0.57	0.80	0.80
	19	0.20	0.20	0.20	0.20
Hyco	20	0.00	0.00	0.00	0.00
	21	0.35	0.40	0.40	0.09
	22	0.00	0.20	0.20	0.20
	23	0.20	0.20	0.20	0.20

Figure 1. Map of Roanoke River Basin with locations for habitat sampling during the 2003 field season. Data were collected about once every river kilometer, where navigable, until the lowermost dam was reached on each river.

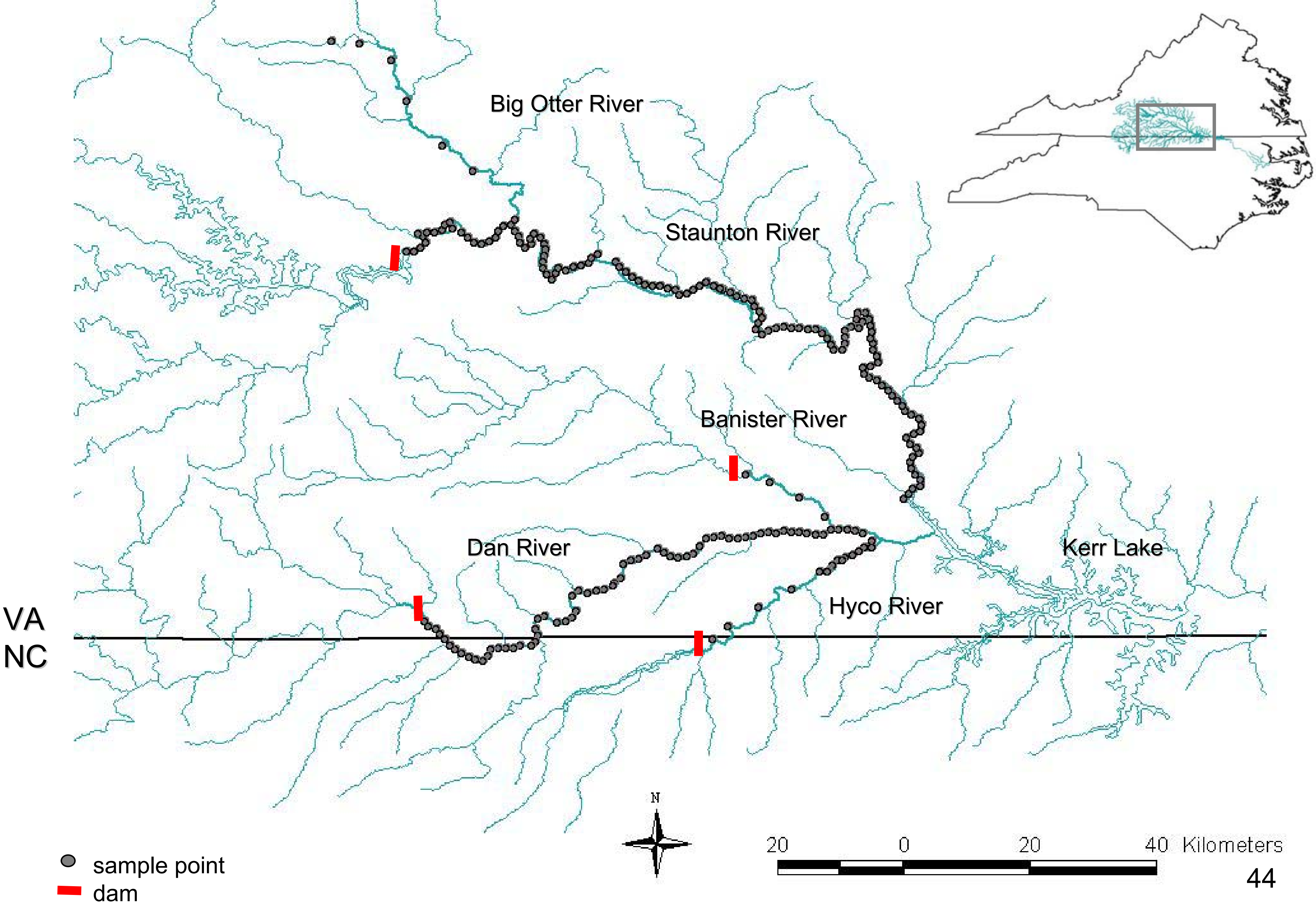


Figure 2. Roanoke River Basin with monthly circuit sampling sites represented with crosshatched circles. Sites were visited from October 2003 to August 2004.

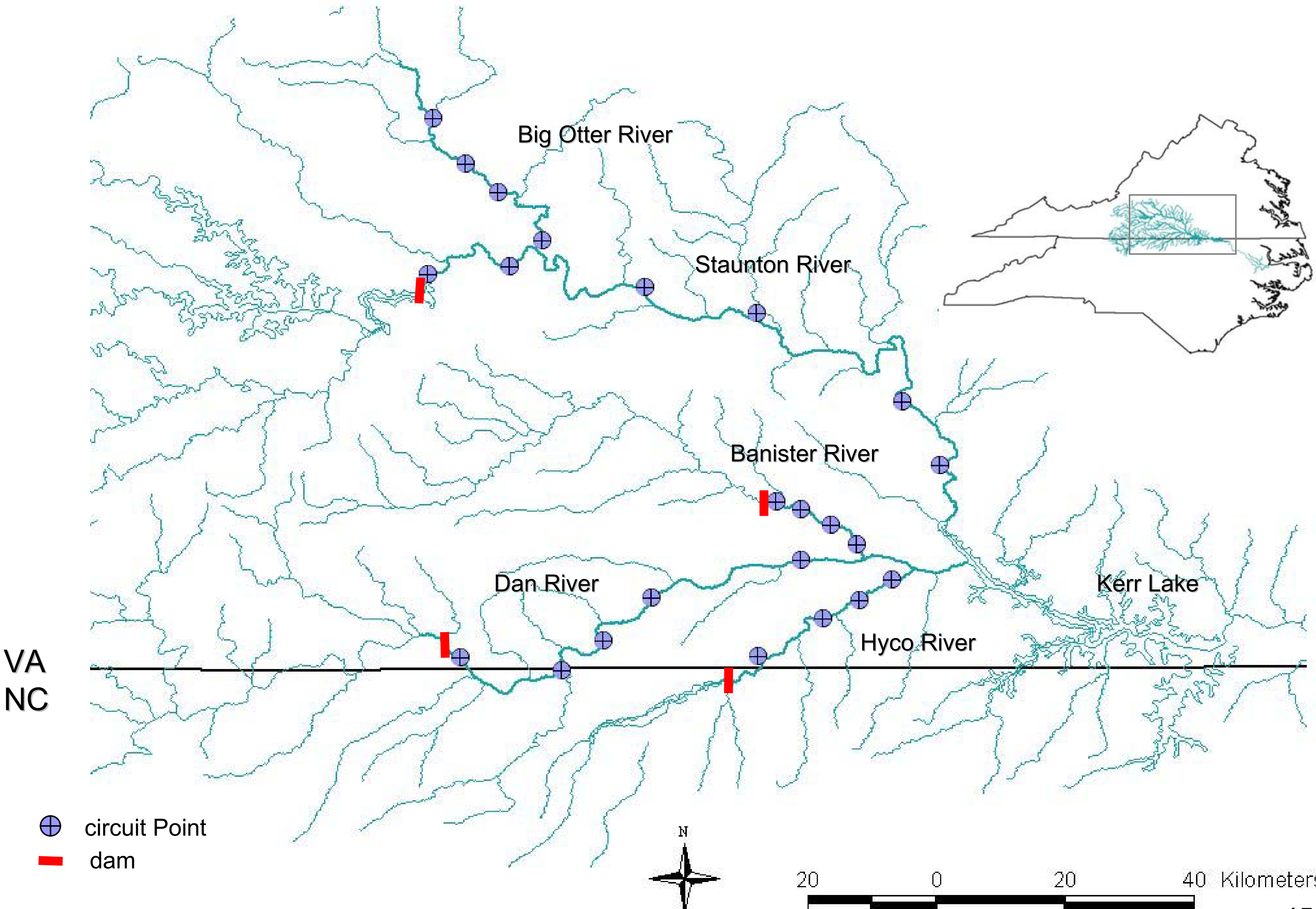


Figure 3. Suitability curves for Stier and Crance (1985) Habitat Suitability Index (HSI) model (used in Model 1 calculations)

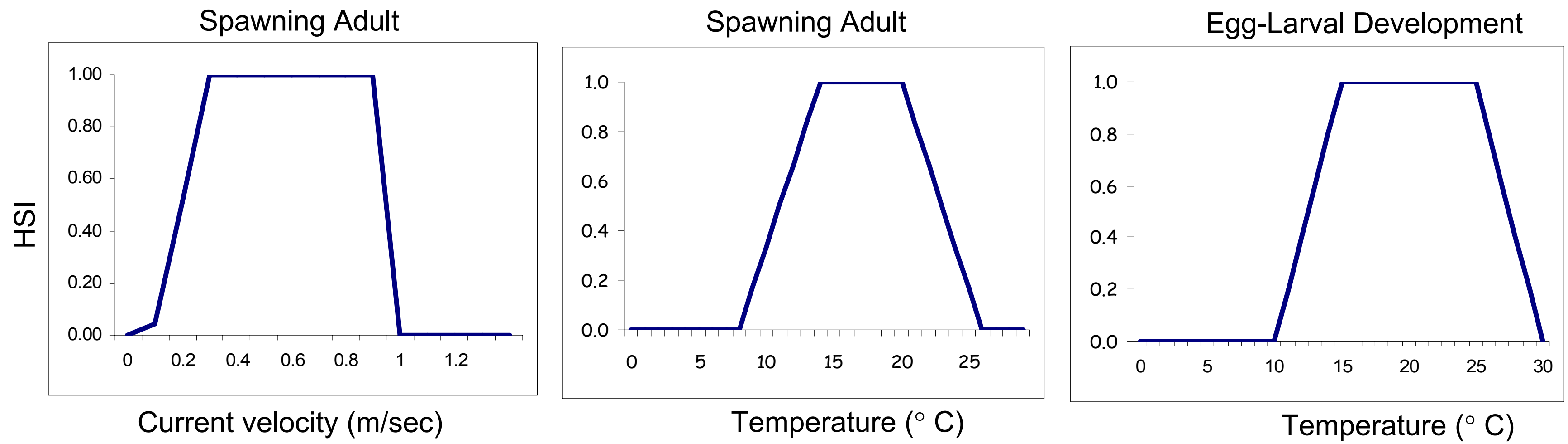


Figure 4. Suitability curves for modified Habitat Suitability Index (HSI) models. Model 2 uses the IFIM bottom substrate component used by Stier and Crance (1985). Model 3 uses an estimated suitability pattern based on spawning sites in the Neuse River (Beasley and Hightower 2000; Bowman and Hightower 2001). Both Model 1 and 2 use the modified SI curve for temperature (Ross et al. 1993a; Bilkovic et al. 2002).

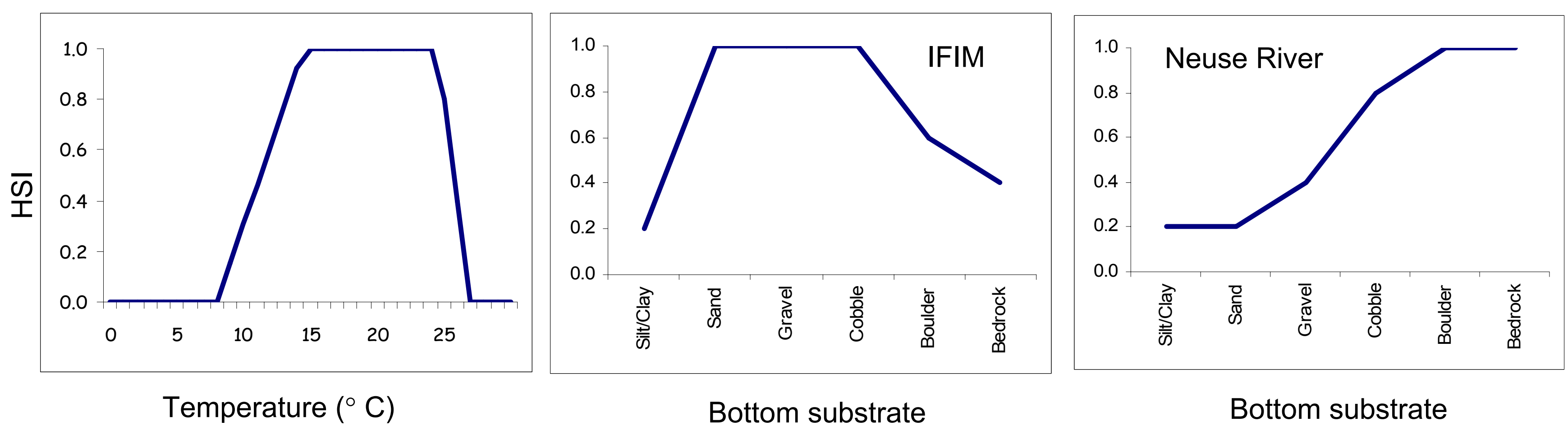


Figure 5. Dominant bottom substrate detected at mid-channel sites in the upper Roanoke basin during the 2003 field season.

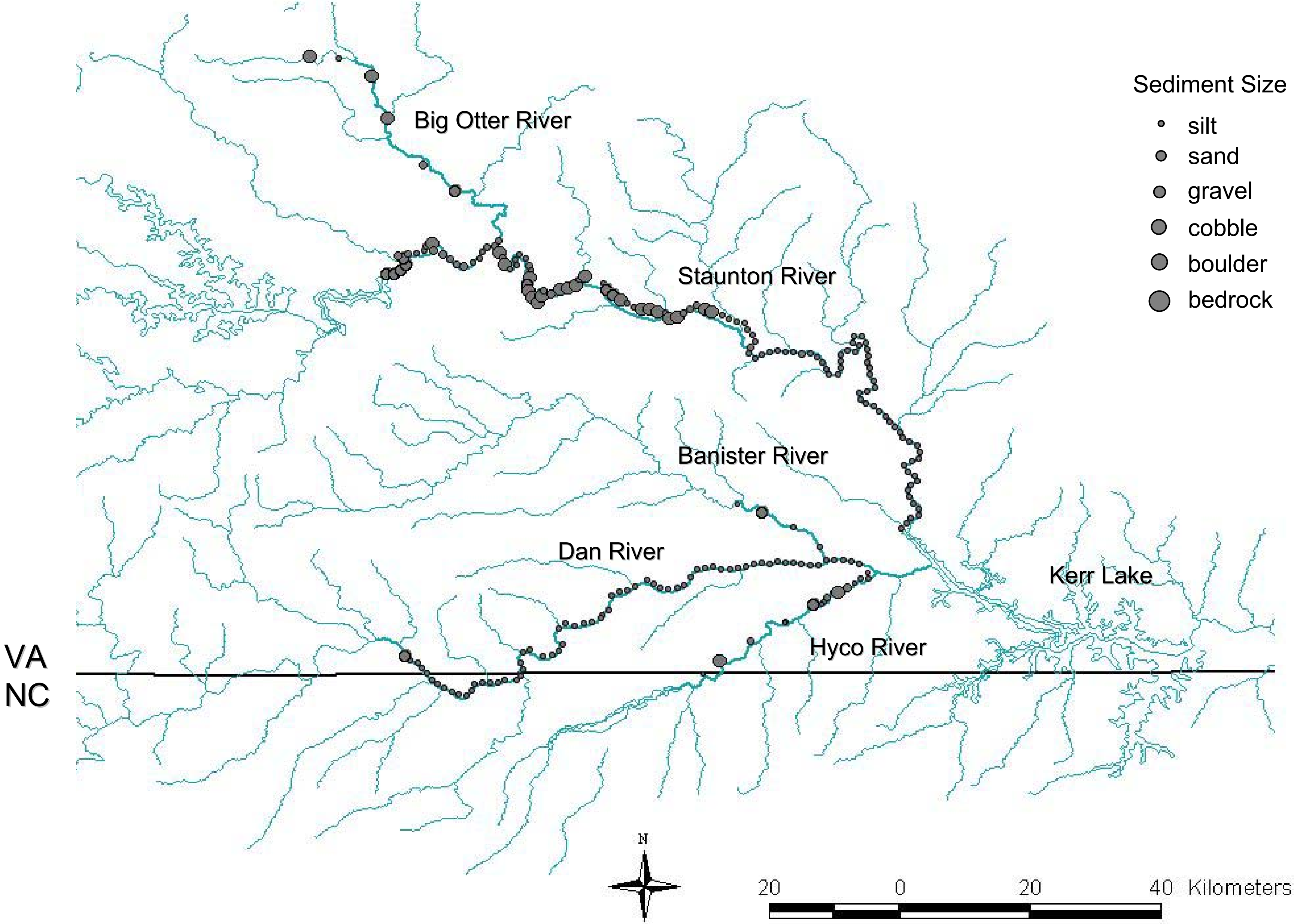


Figure 6. Longitudinal classification for sites in the upper Roanoke basin as determined during the 2003 field season.

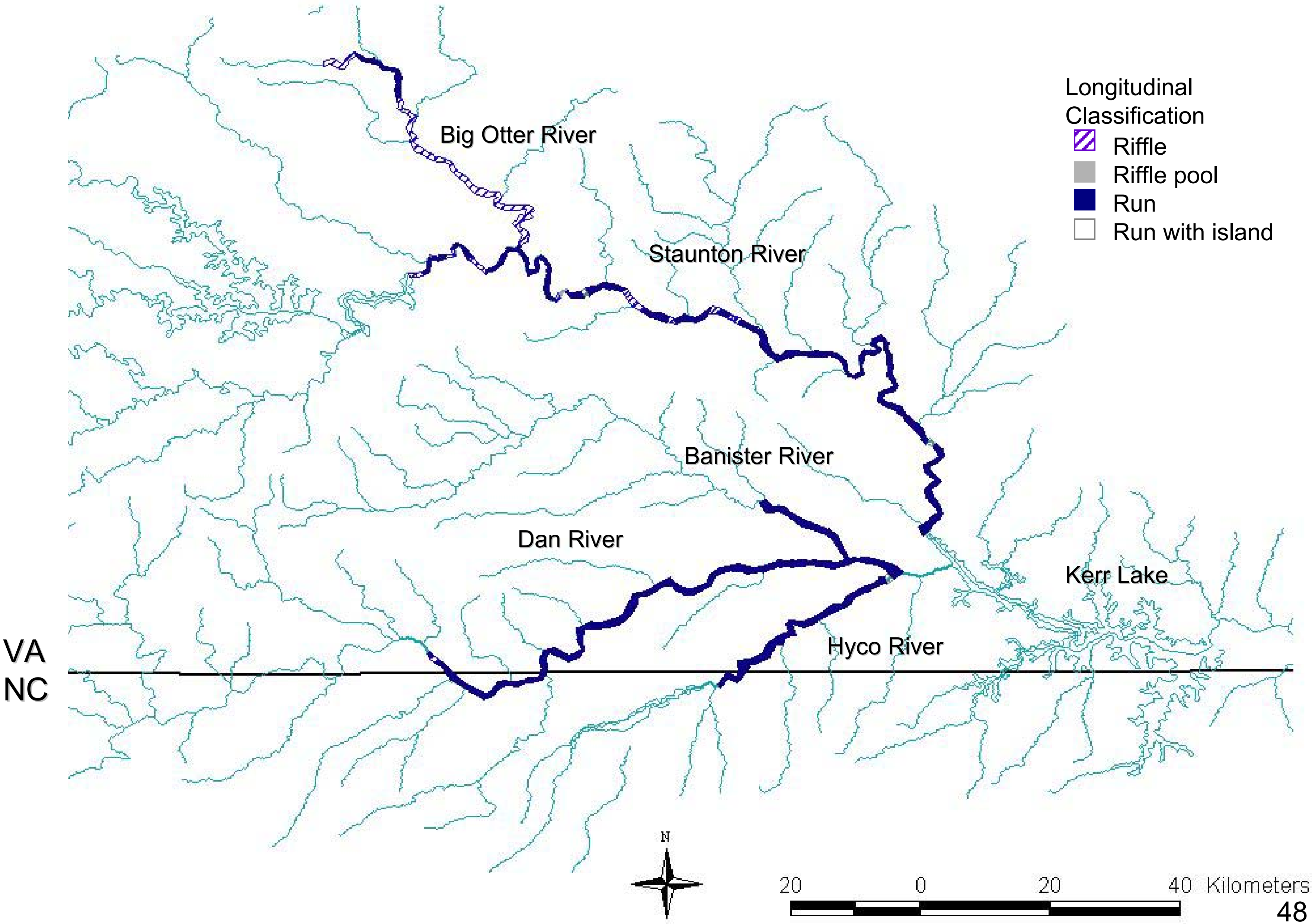


Figure 7. Presence or absence of woody debris at sites in the upper Roanoke basin during the 2003 field season.

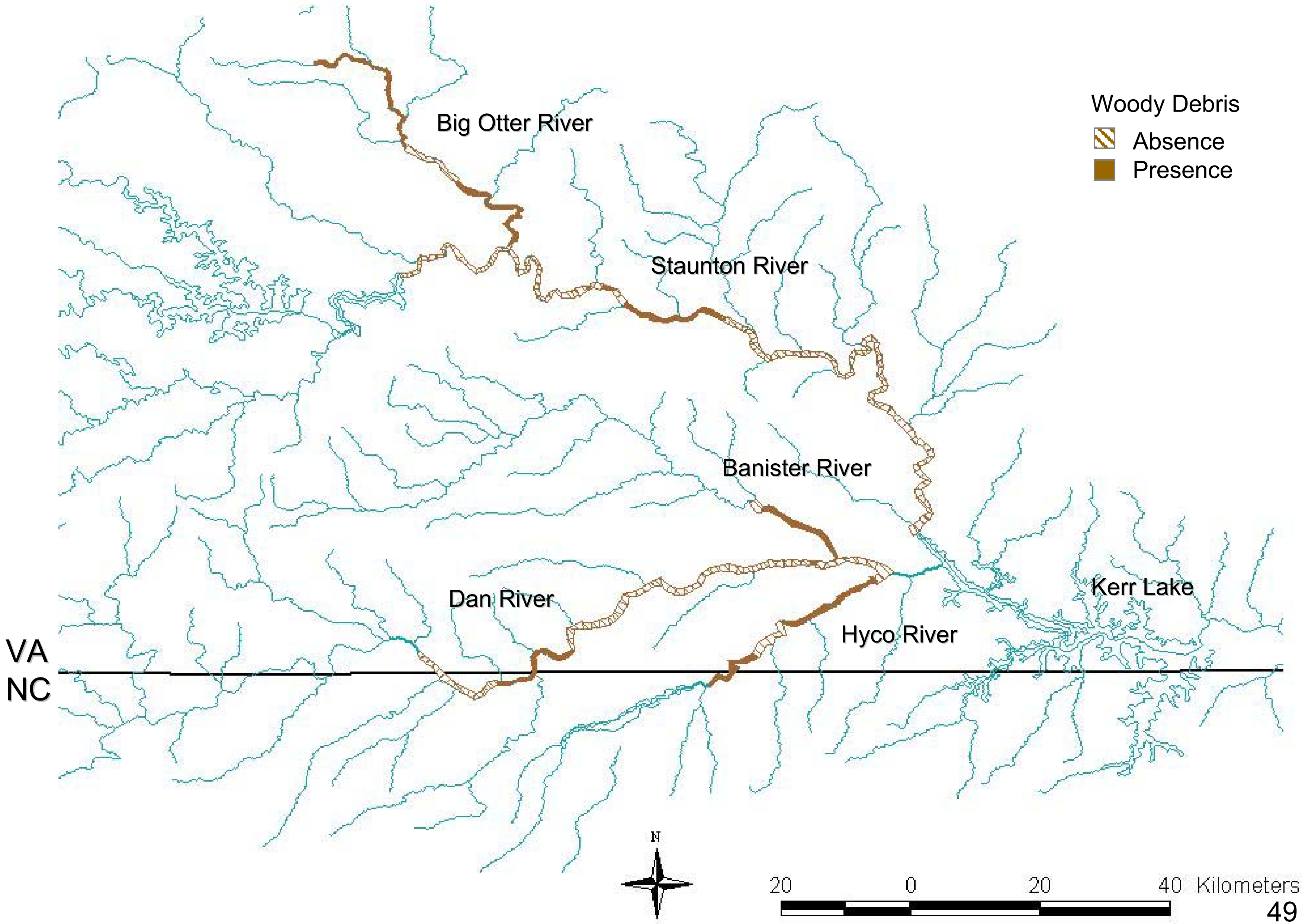


Figure 8. Percentage of the river with overhanging vegetation at sites in the upper Roanoke basin during the 2003 field season.

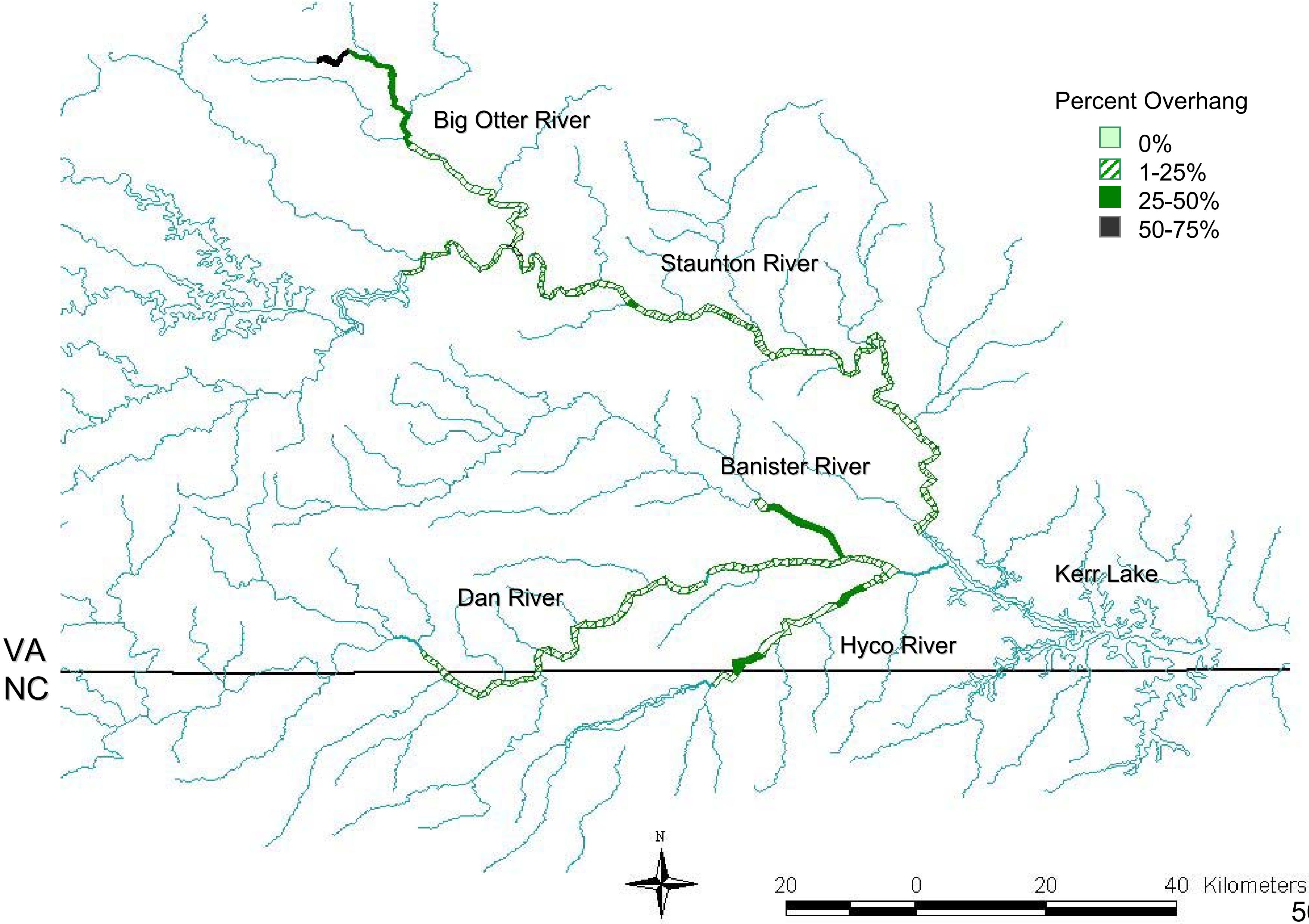


Figure 9. Mean daily discharge values and historical mean levels in cubic feet per second (cfs) for days when circuit sampling was conducted.

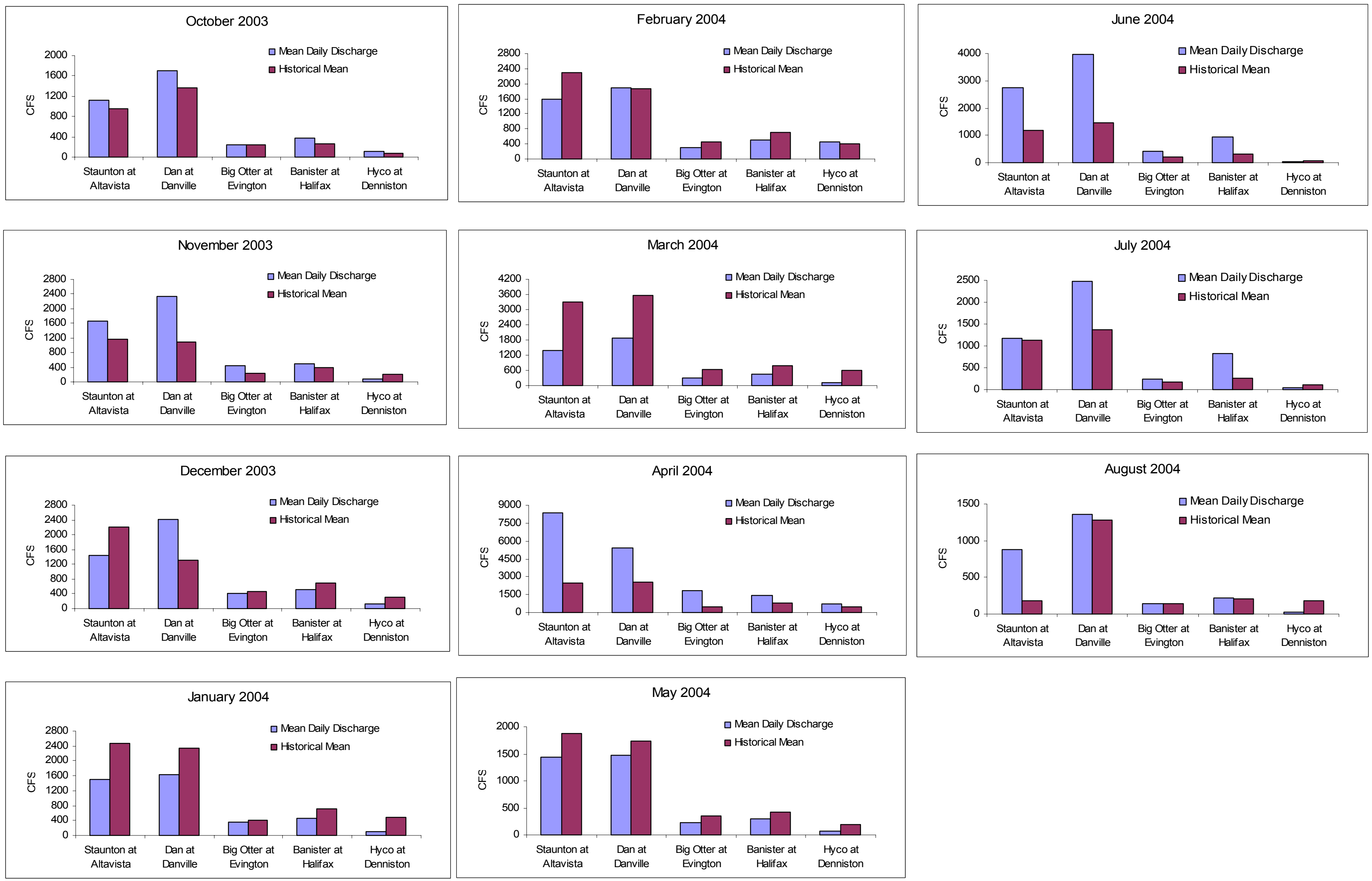


Figure 10. Least Squares Means by river for water quality variables measured during circuit sampling from October 2003 through August 2004. Error bars denote ±1 SE. The horizontal lines above the plots were constructed using Tukey's HSD from the analysis of variance. Sites connected by the same line height are not significantly different from each other.

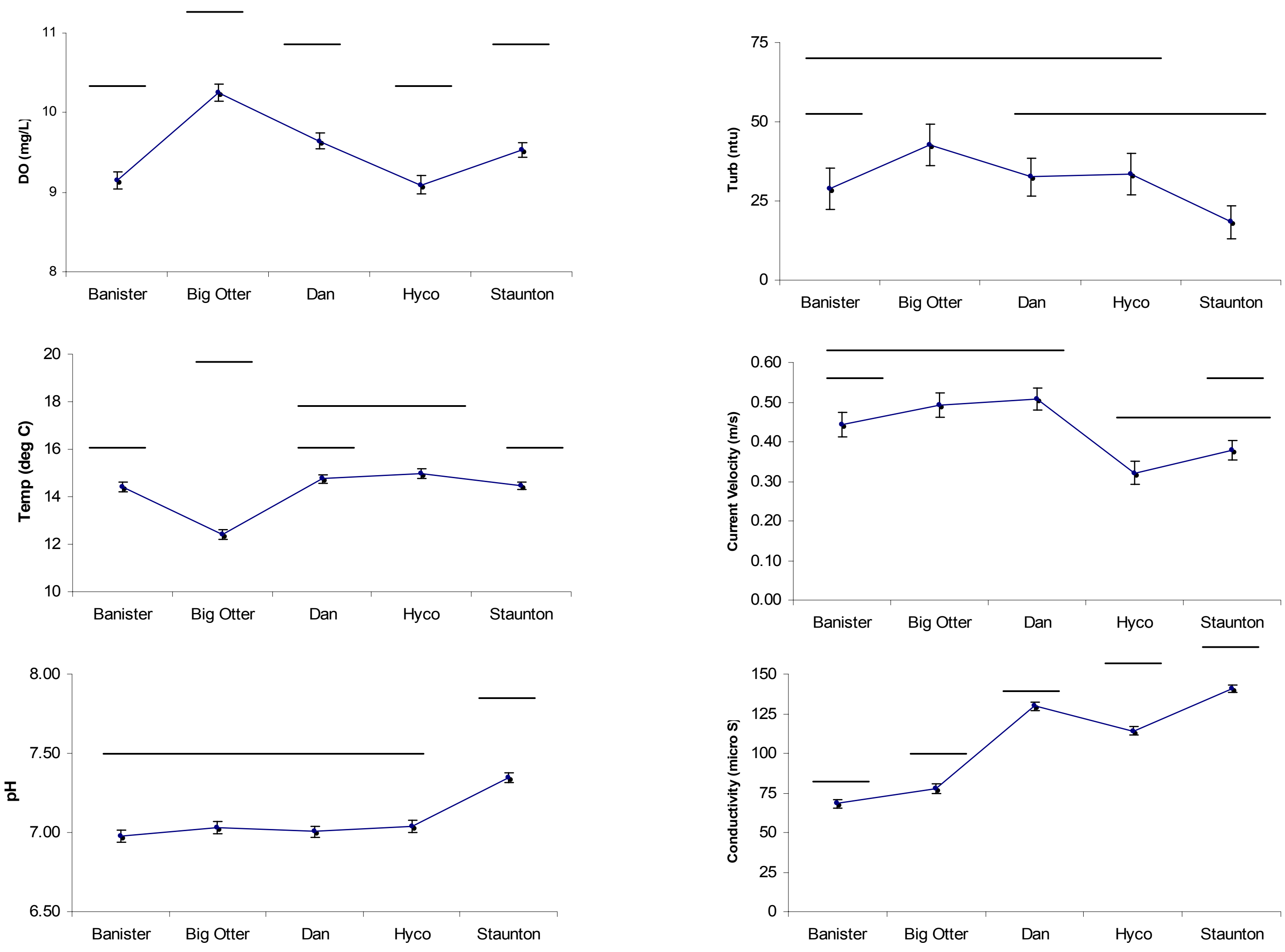


Figure 11. Relationship between Temperature and Dissolved Oxygen Data collected during 2003 and 2004.

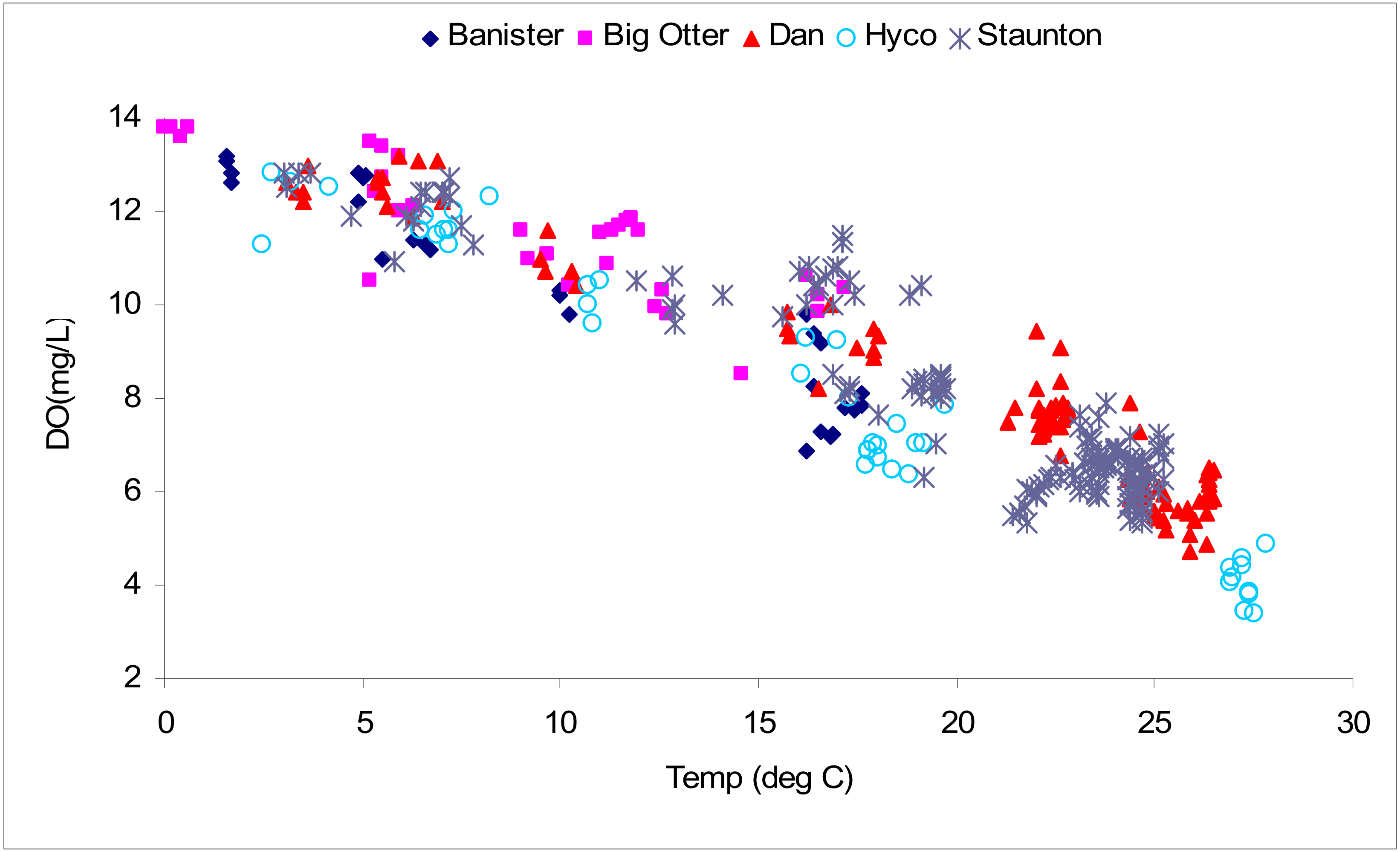


Figure 12. March current velocity (m/s) shown. Current Velocity legend based on suitable ranges for spawning adults defined by Stier and Crance (1985), data were collected during 2004 circuit sampling.

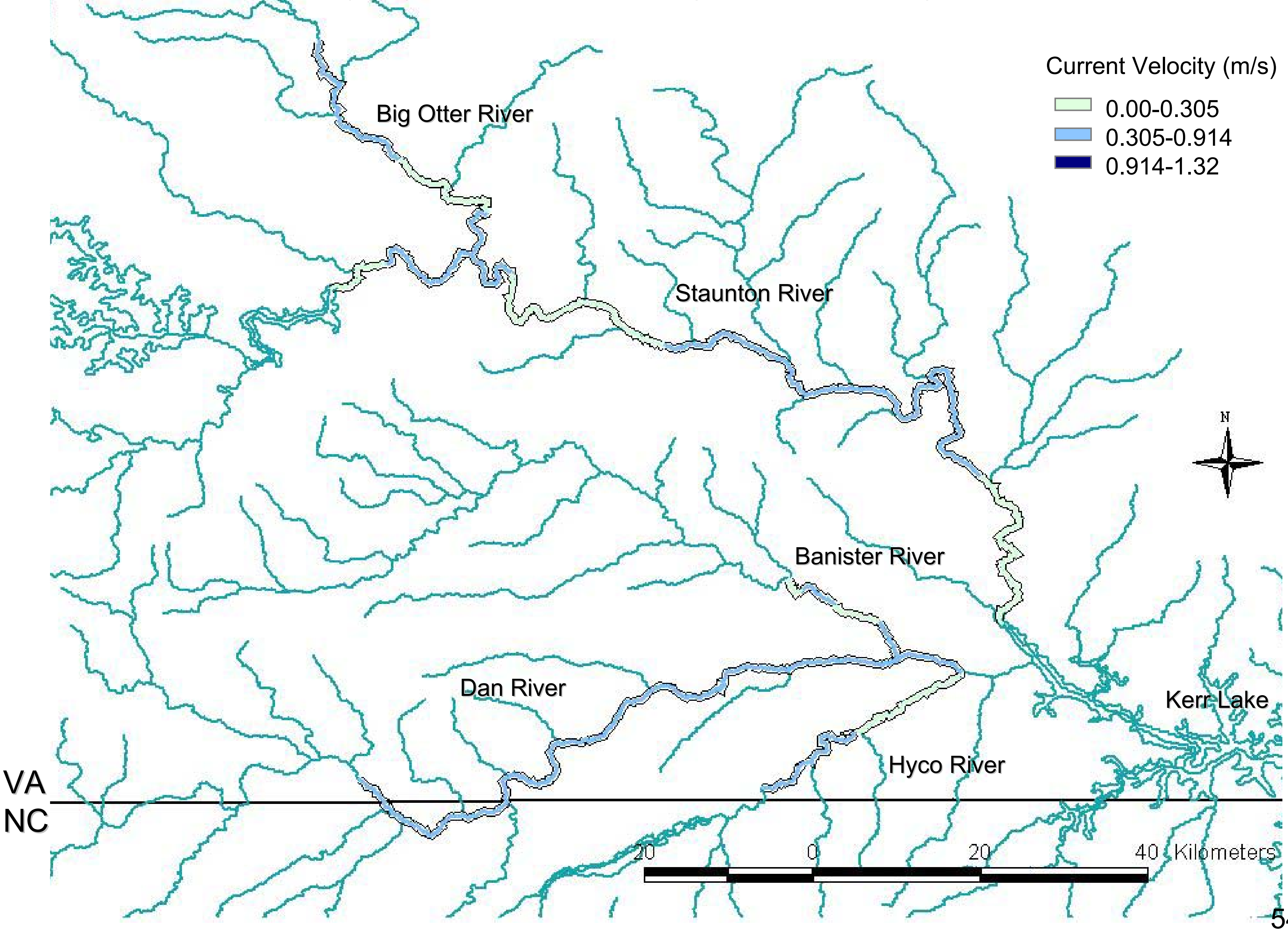


Figure 13. April current velocity (m/s) shown. Current Velocity legend based on suitable ranges for spawning adults defined by Stier and Crance (1985), data were collected during 2004 circuit sampling.

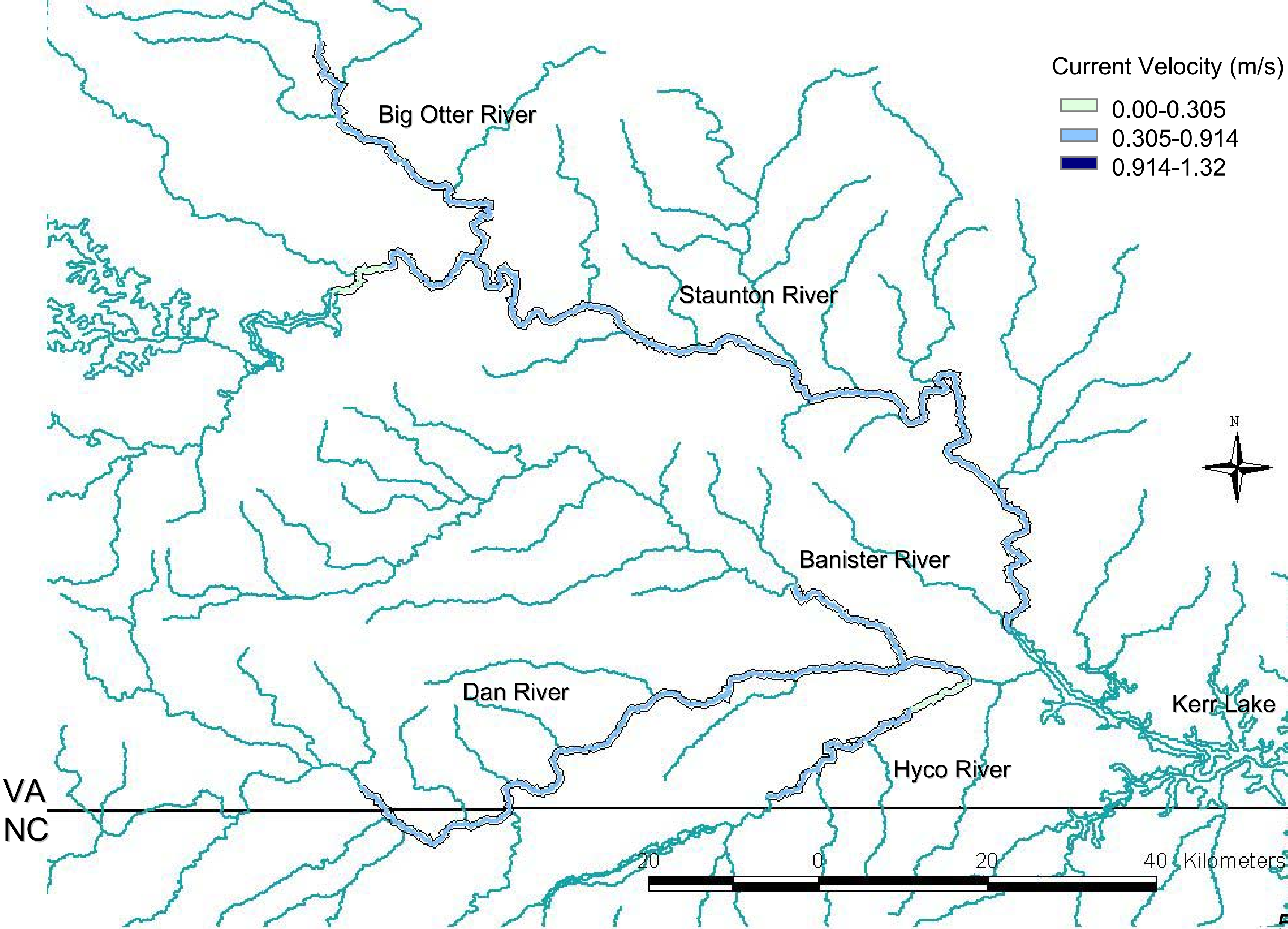


Figure 14. May current velocity (m/s) shown. Current Velocity legend based on suitable ranges for spawning adults defined by Stier and Crance (1985), data were collected during 2004 circuit sampling.

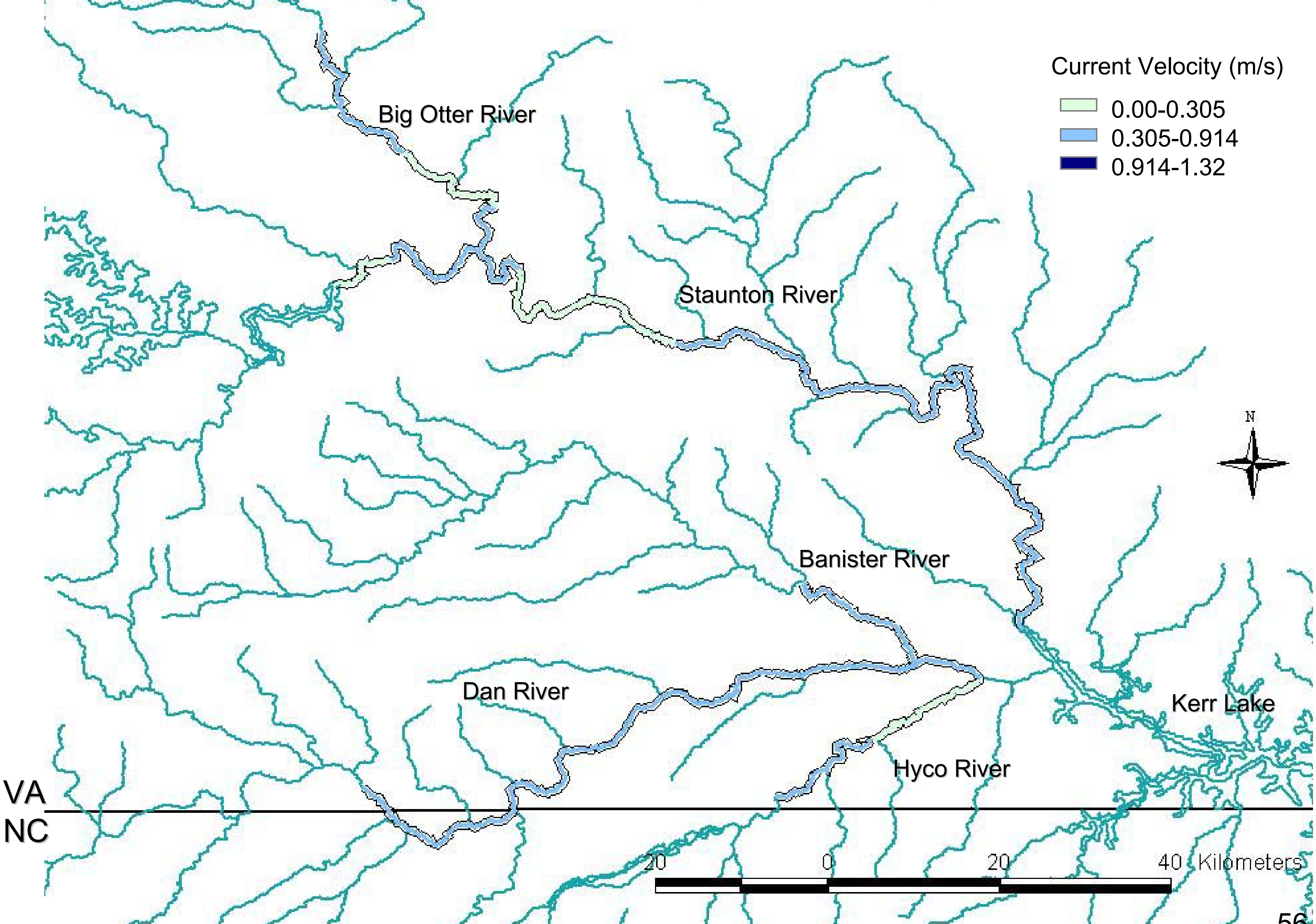


Figure 15. June current velocity (m/s) shown. Current Velocity legend based on suitable ranges for spawning adults defined by Stier and Crance (1985), data were collected during 2004 circuit sampling.

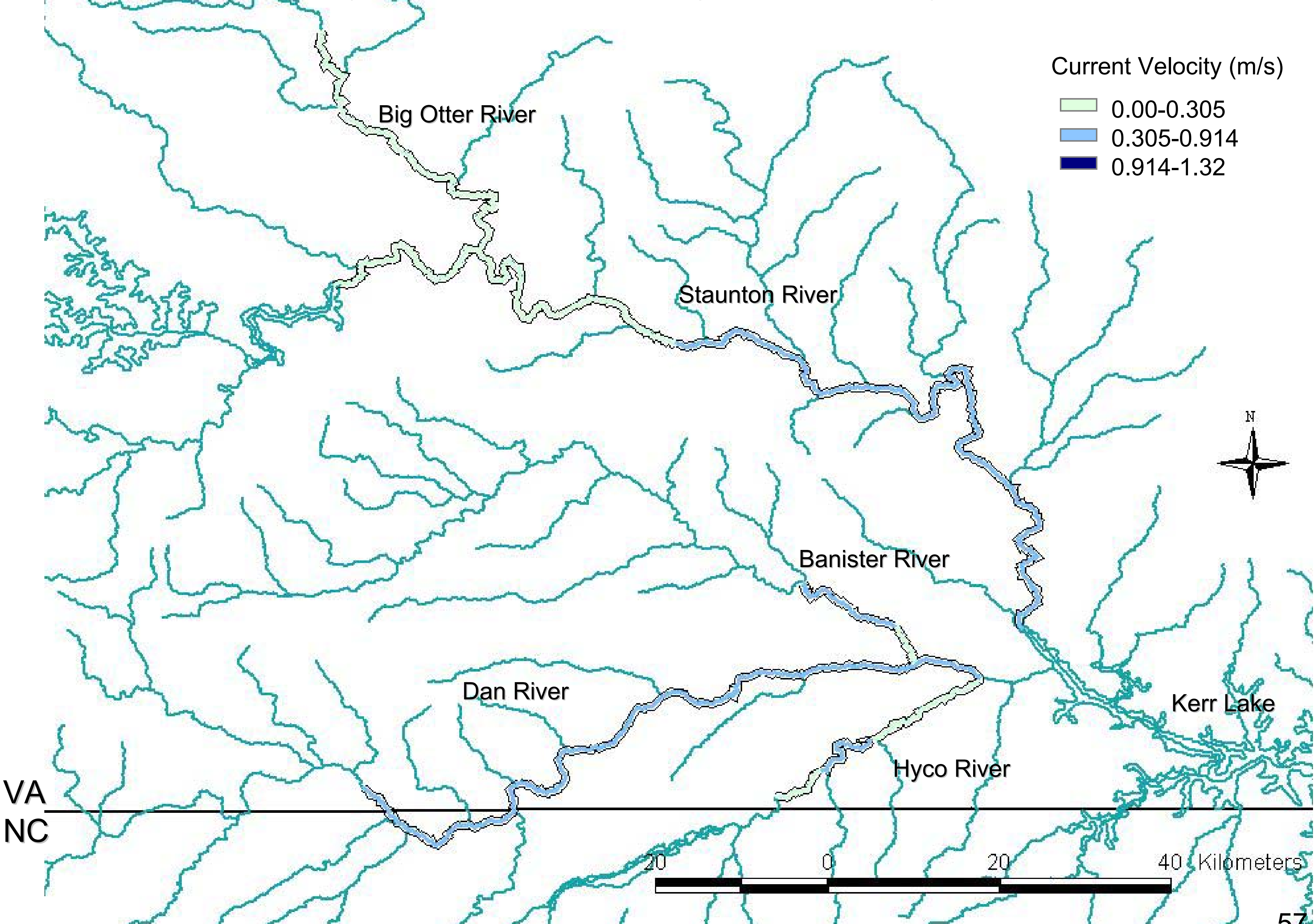


Figure 16. March Habitat Suitability Values shown, calculated with Stier and Crance (1985) HSI Model (Model 1). Data were collected during 2004 circuit sampling.

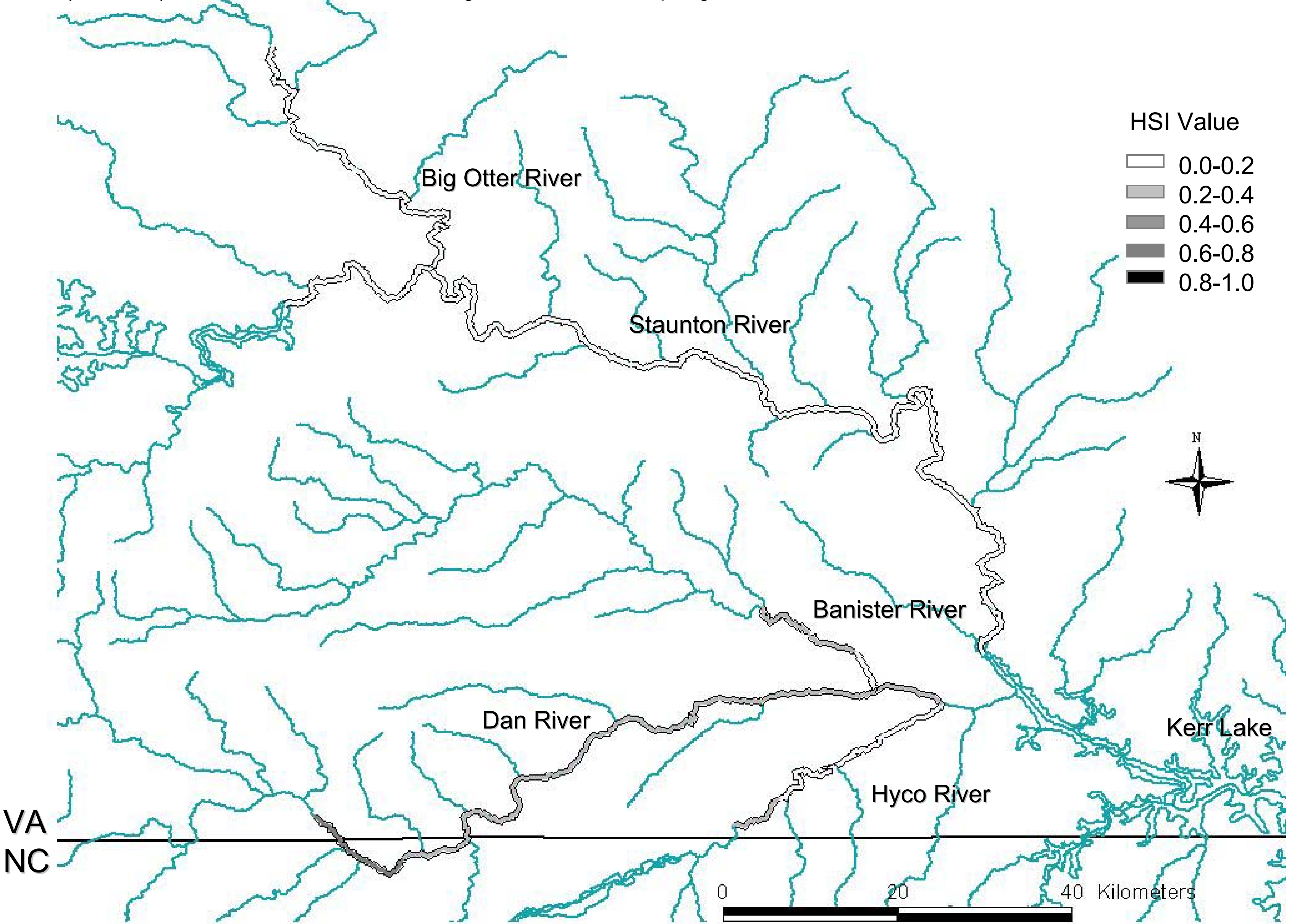


Figure 17. April Habitat Suitability Values shown, calculated with Stier and Crance (1985) HSI Model (Model 1). Data were collected during 2004 circuit sampling.

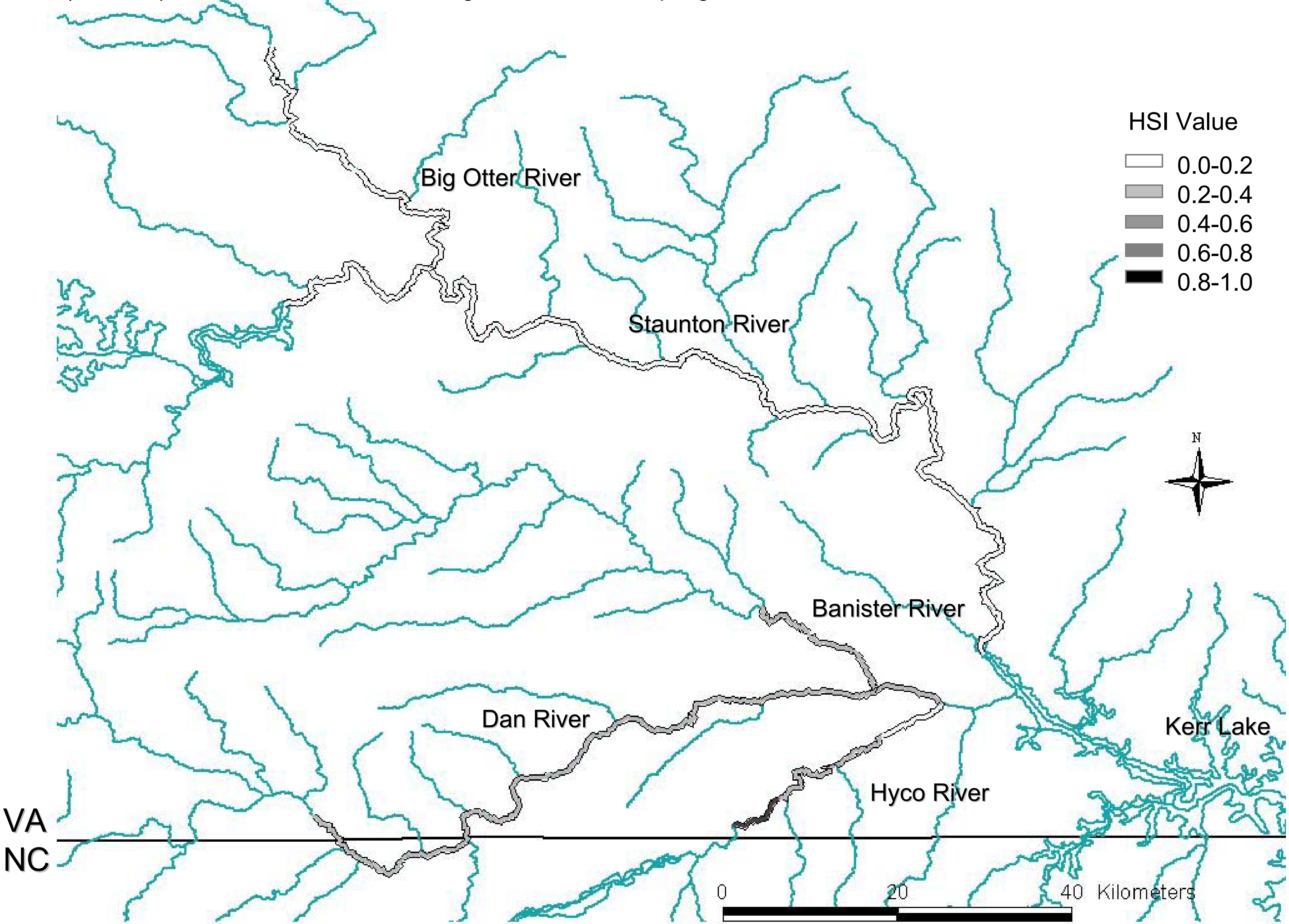


Figure 18. May Habitat Suitability Values shown, calculated with Stier and Crance (1985) HSI Model (Model 1). Data were collected during 2004 circuit sampling.

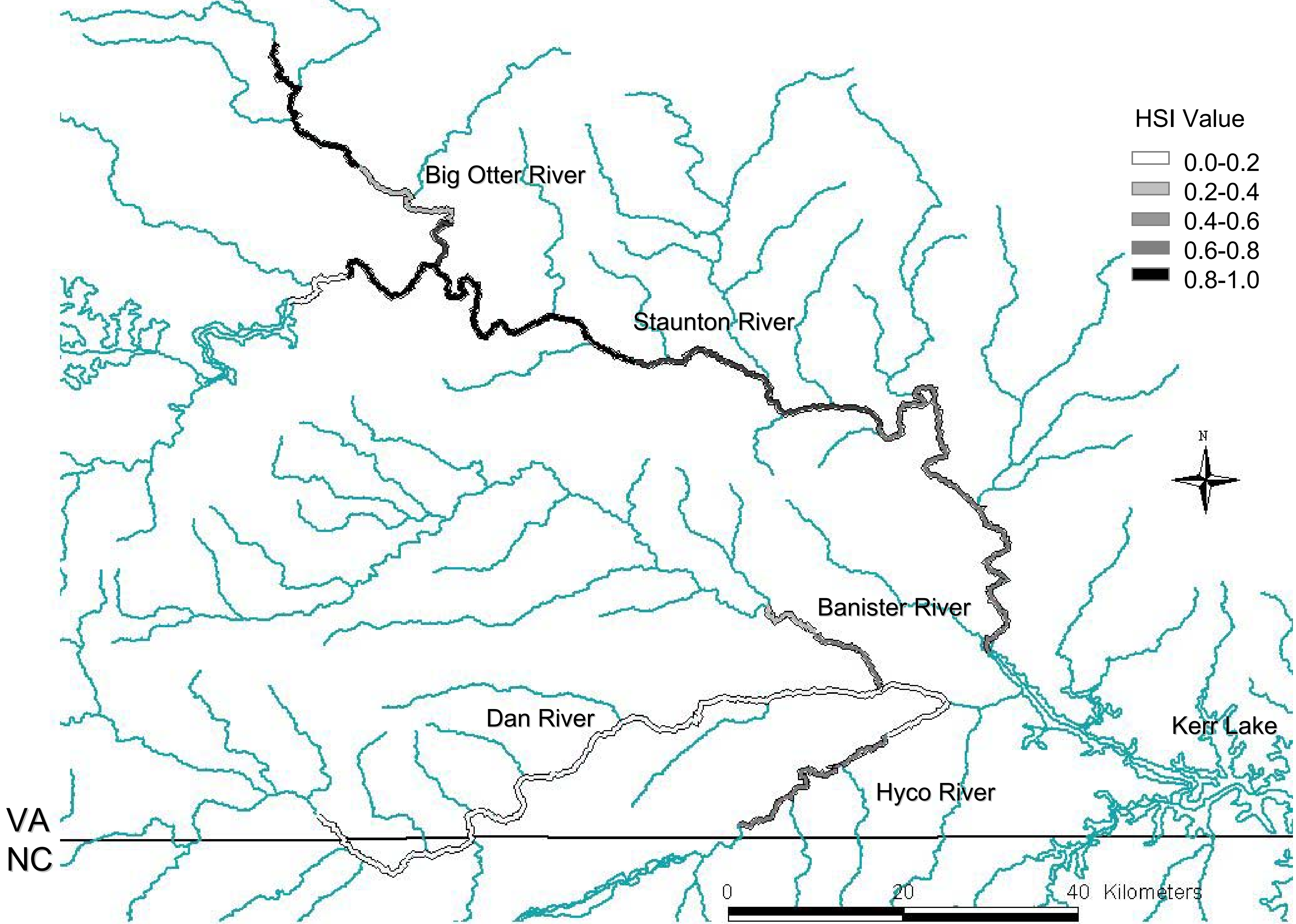


Figure 19. June Habitat Suitability Values shown, calculated with Stier and Crance (1985) HSI Model (Model 1). Data were collected during 2004 circuit sampling.

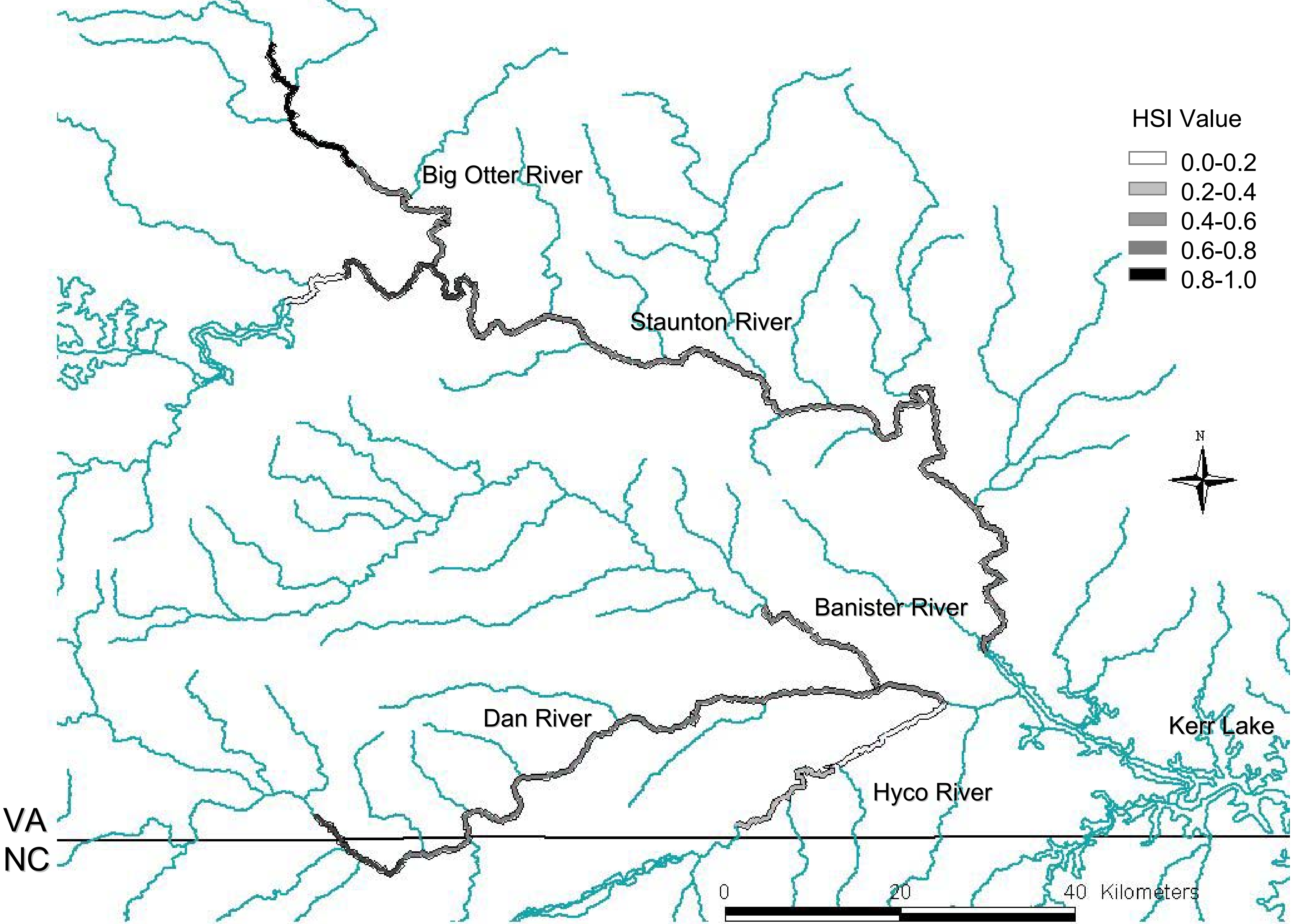


Figure 20. Suitability values determined using the bottom substrate component of the IFIM model (Model 2) for American shad spawning (Stier and Crance 1985)

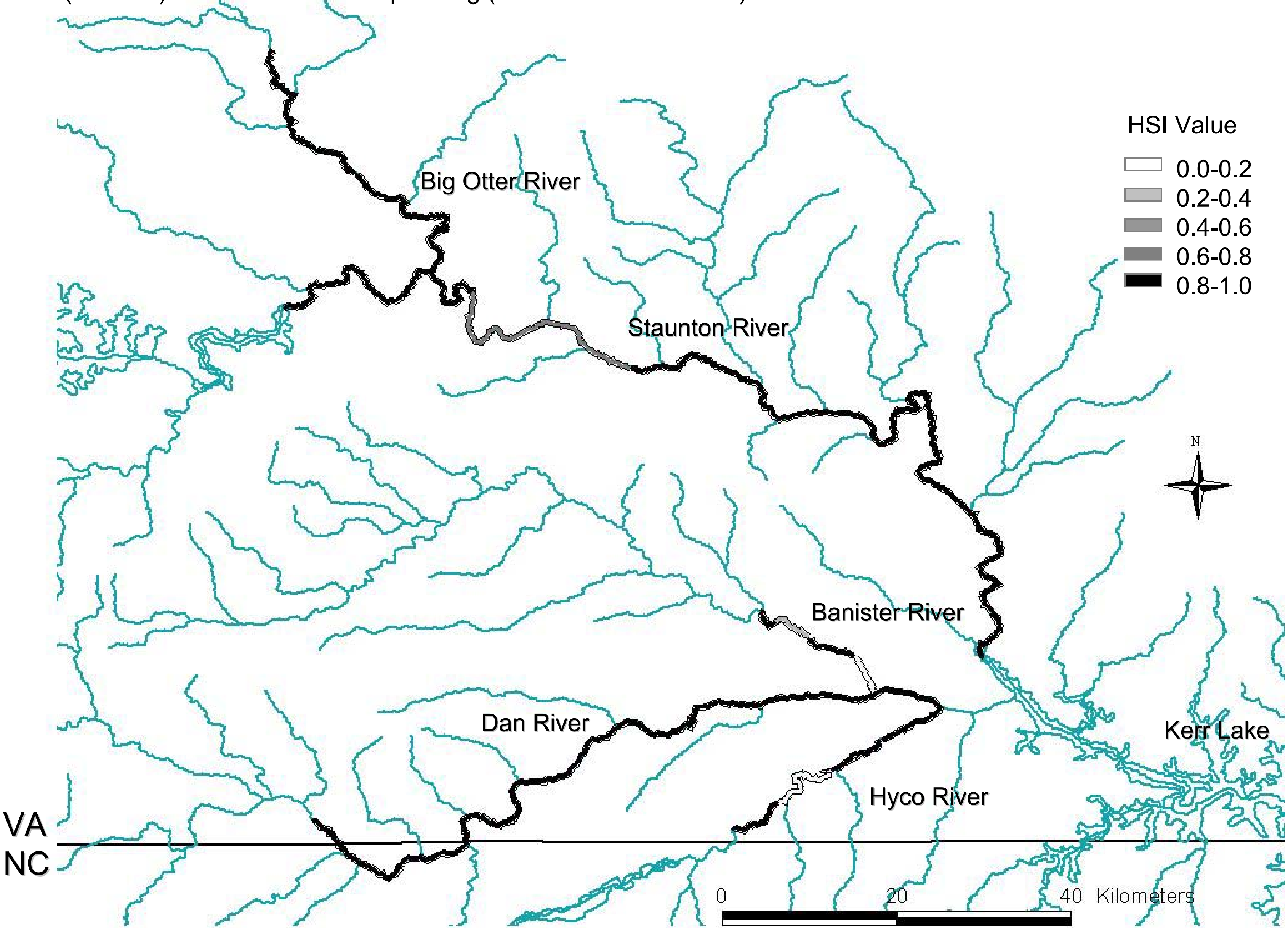


Figure 21. March Habitat Suitability values (Model 2) based on temperature, current velocity, and the IFIM bottom substrate component.

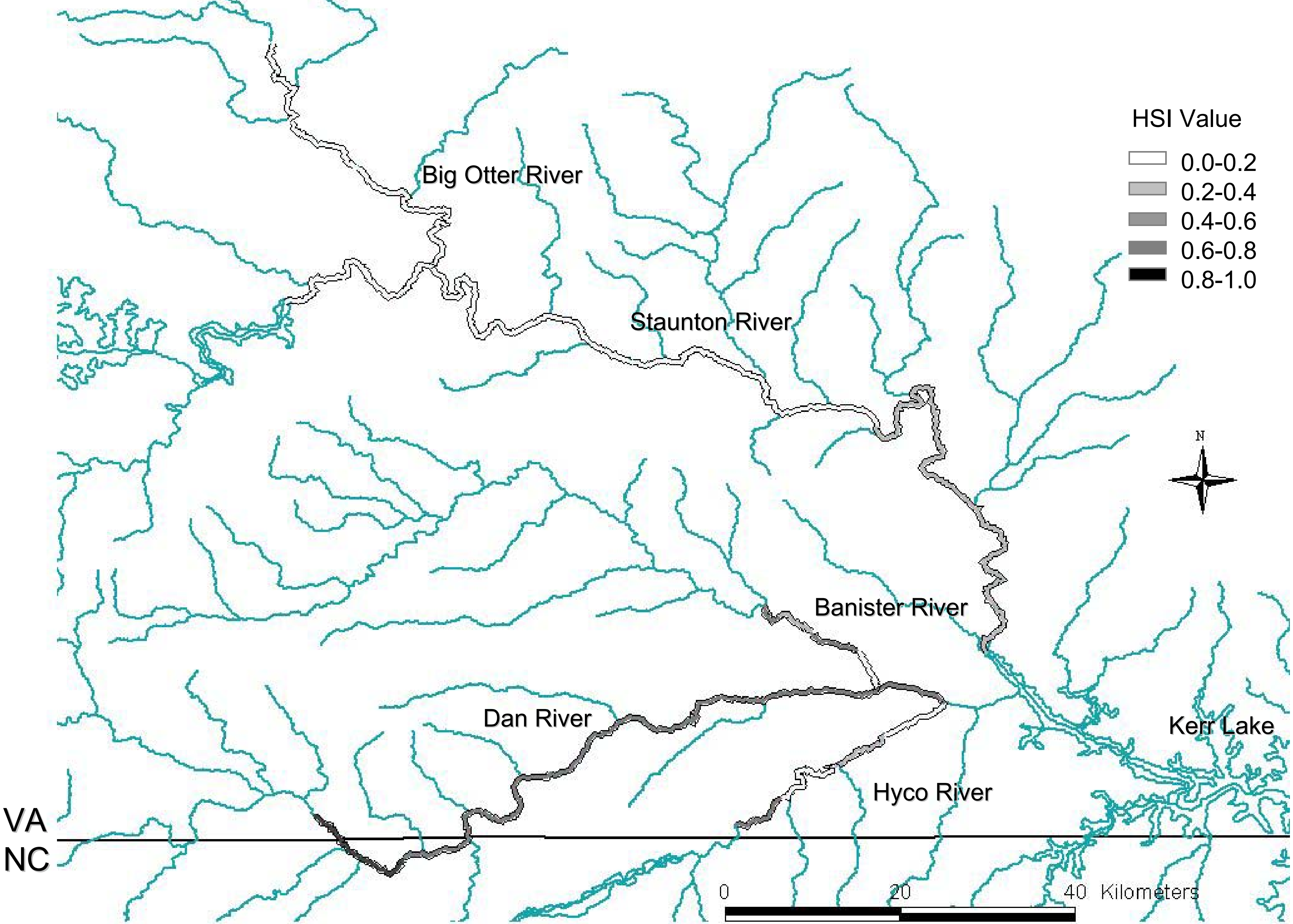


Figure 22. April Habitat Suitability values (Model 2) based on temperature, current velocity, and the IFIM bottom substrate component.

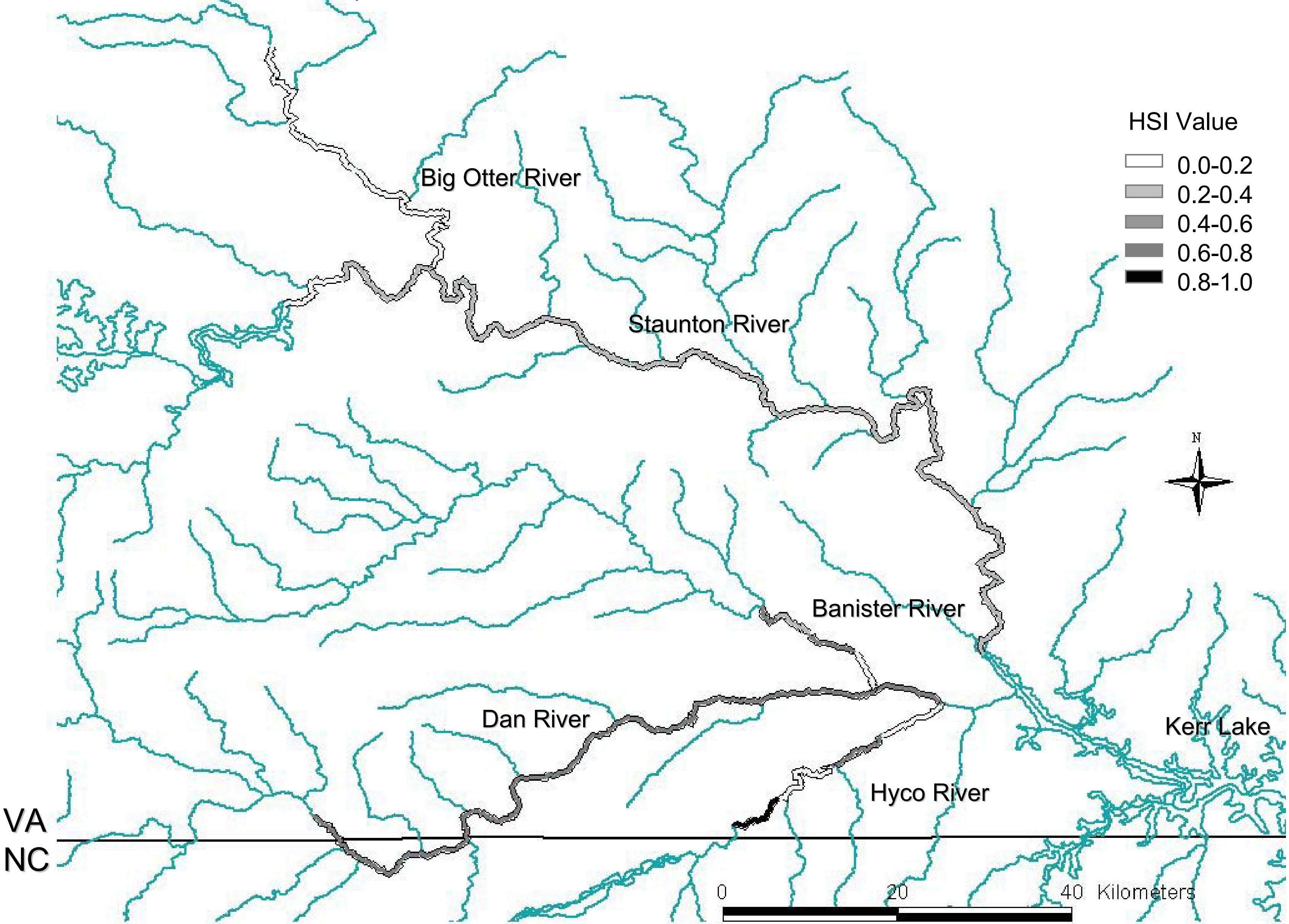


Figure 23. May Habitat Suitability values (Model 2) based on temperature, current velocity, and the IFIM bottom substrate component.

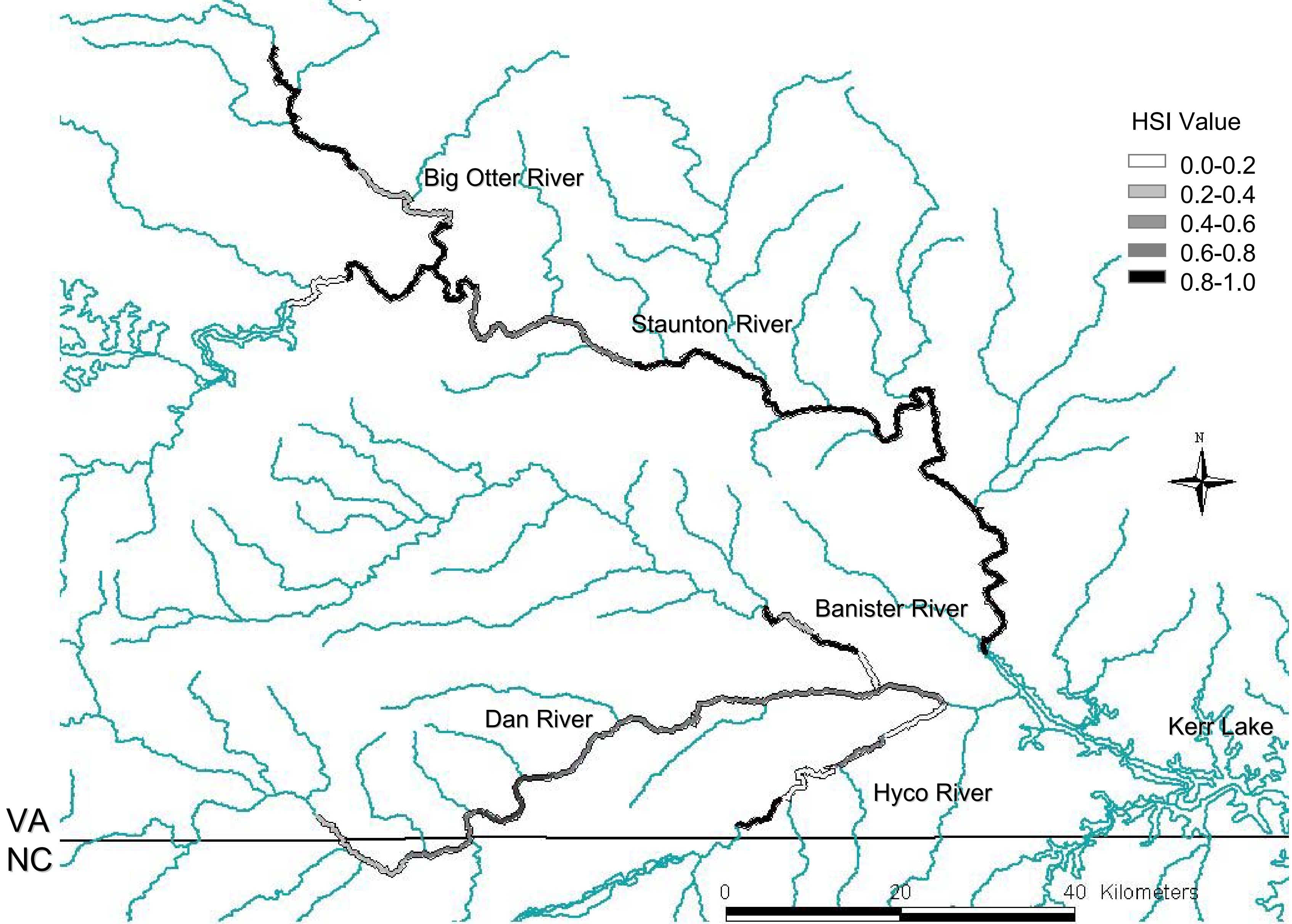


Figure 24. June Habitat Suitability values (Model 2) based on temperature, current velocity, and the IFIM bottom substrate component.

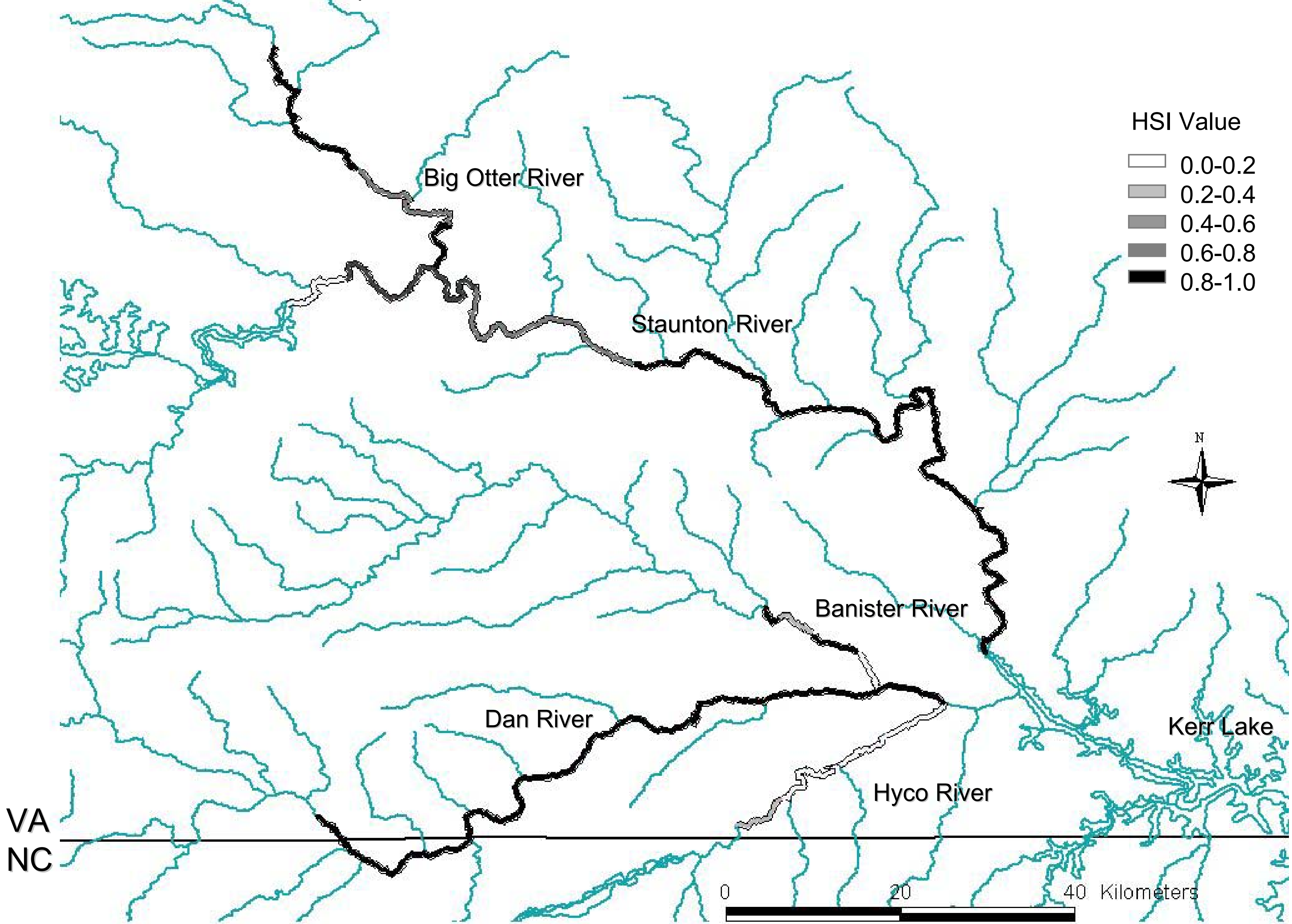


Figure 25. Suitability values for bottom substrate (Model 3), based on research results in the Neuse River (Beasley and Hightower 2000; Bowman and Hightower 2001)

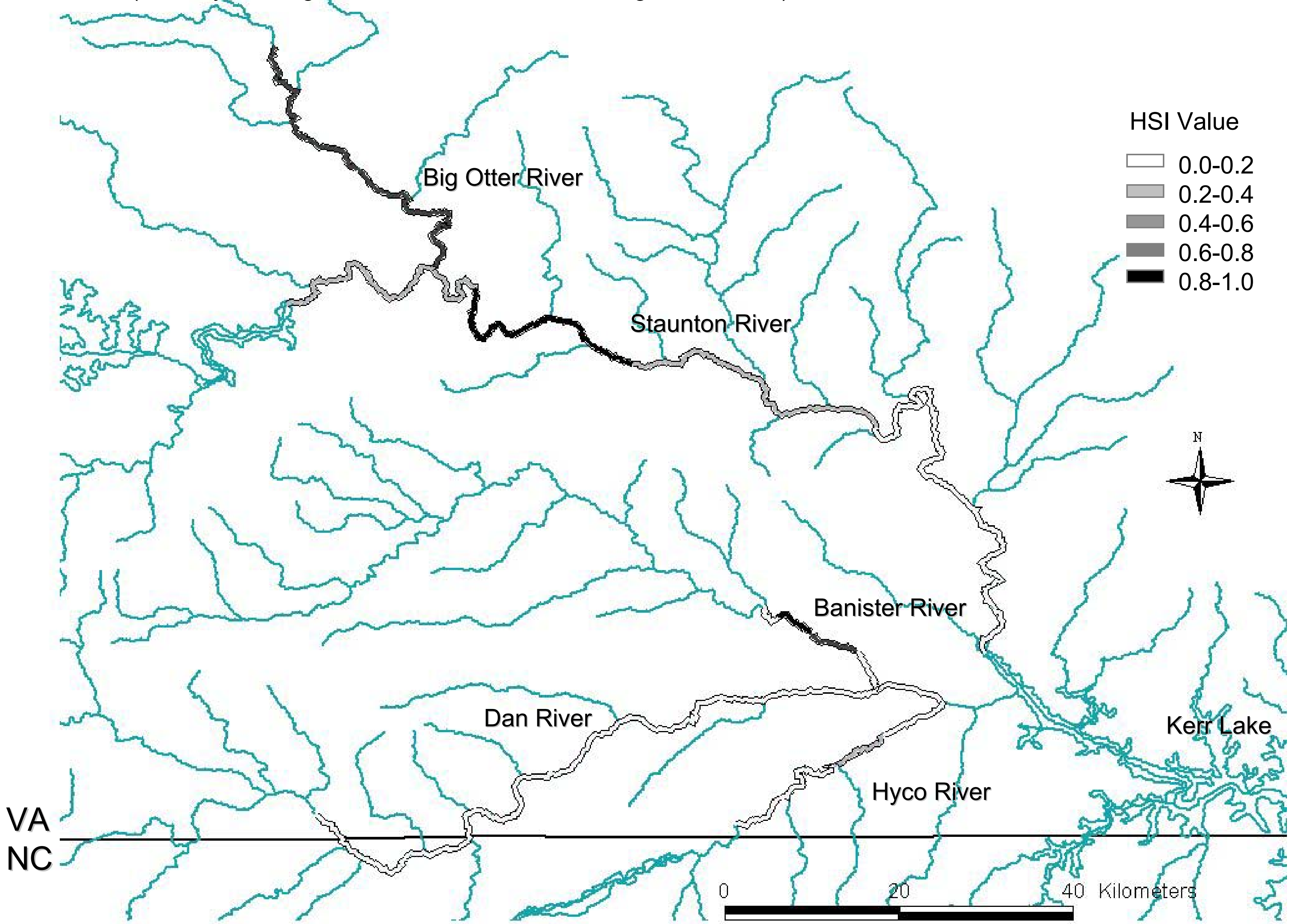


Figure 26. March Habitat Suitability values based on temperature, current velocity, and bottom substrate from Model 3.

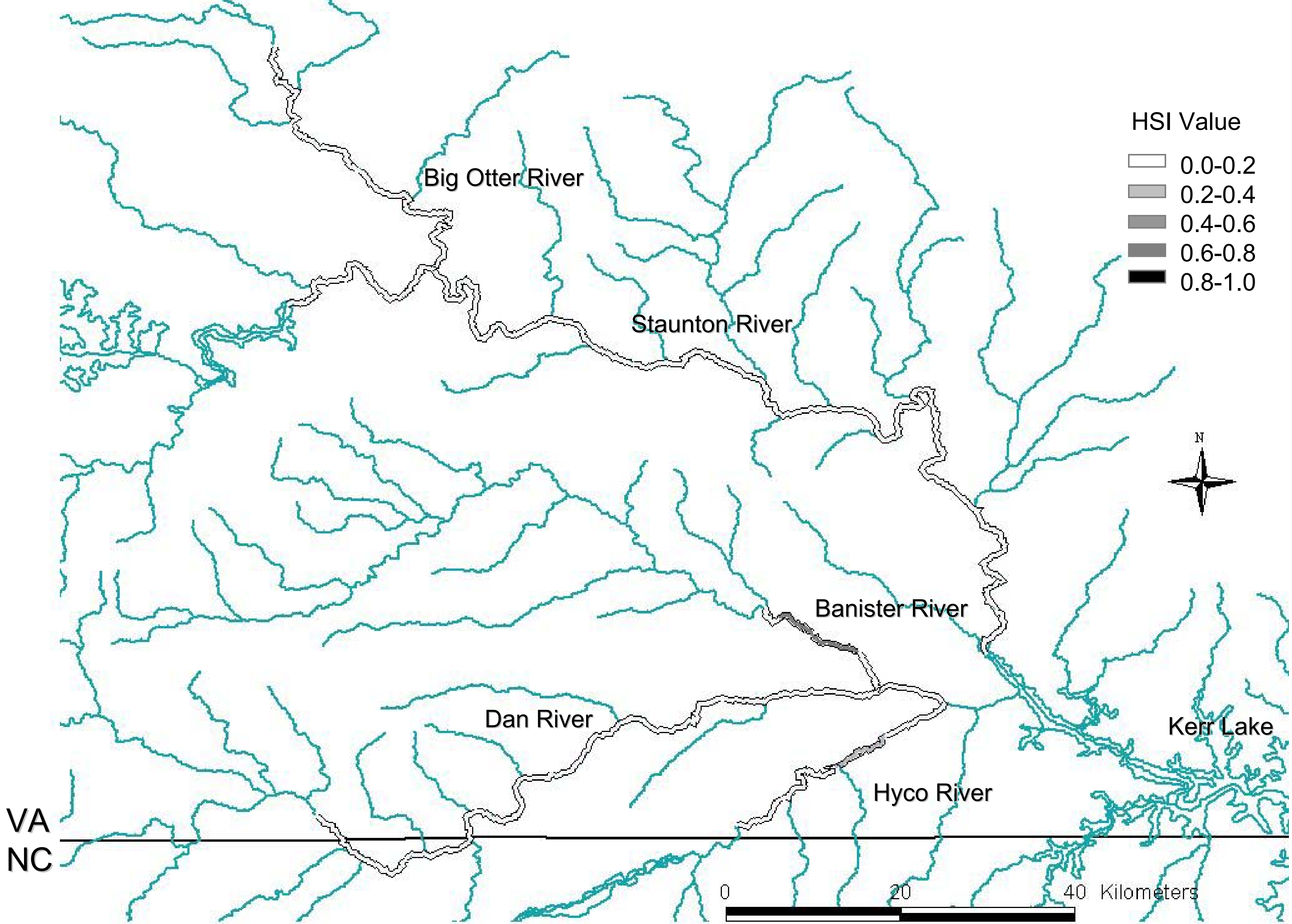


Figure 27. April Habitat Suitability values based on temperature, current velocity, and bottom substrate from Model 3.

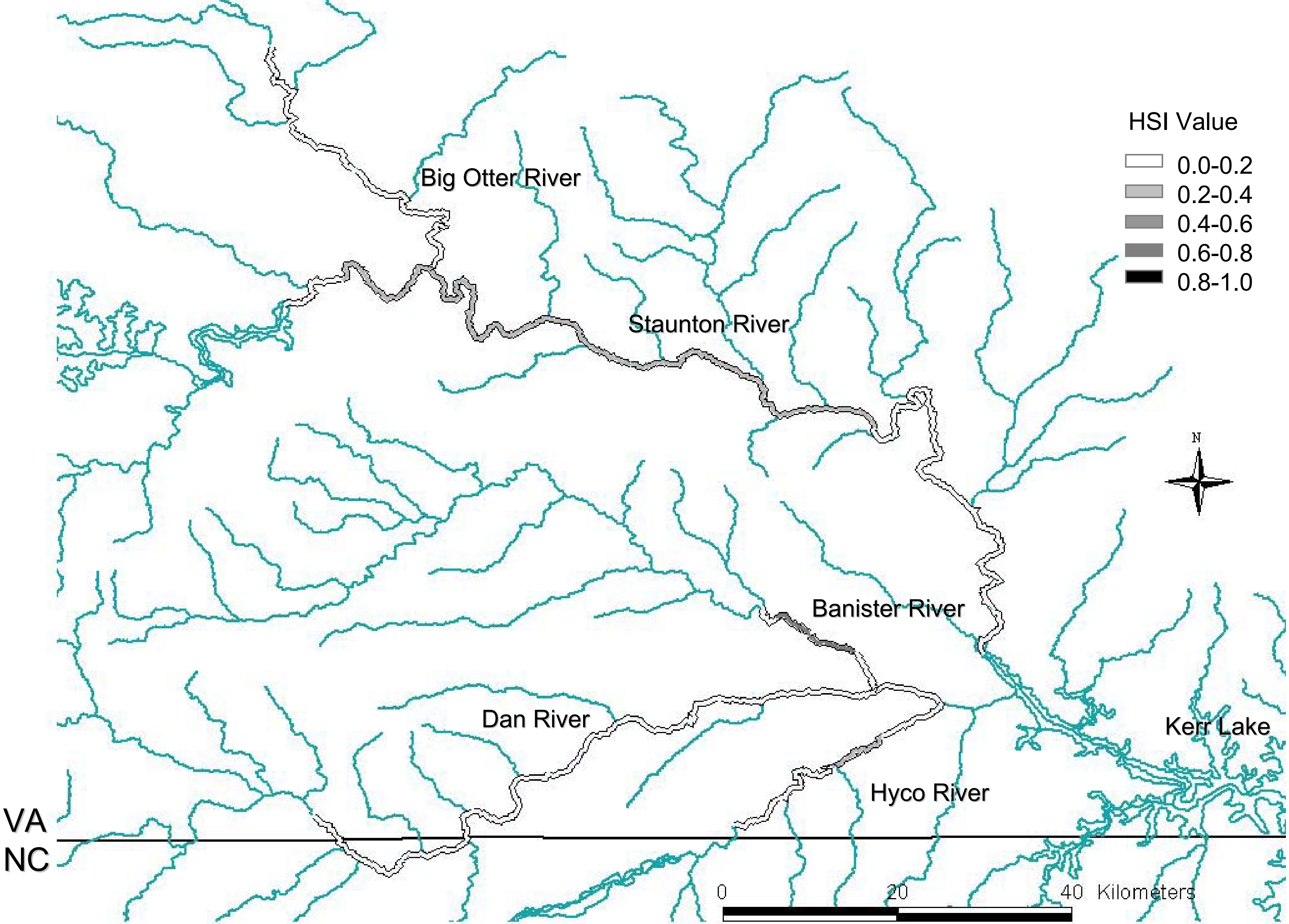


Figure 28. May Habitat Suitability values based on temperature, current velocity, and bottom substrate from Model 3.

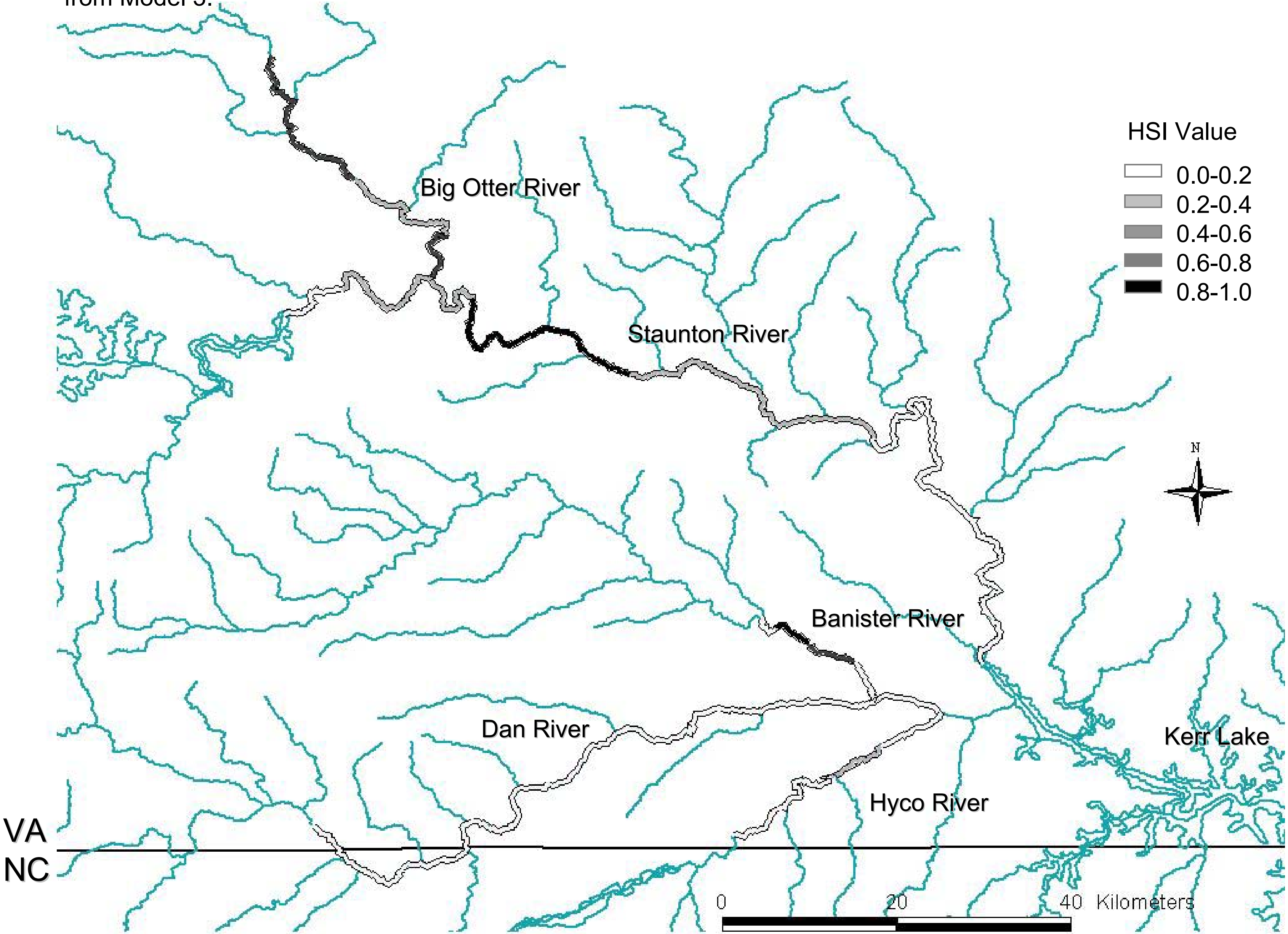


Figure 29. June Habitat Suitability values based on temperature, current velocity, and bottom substrate from Model 3.

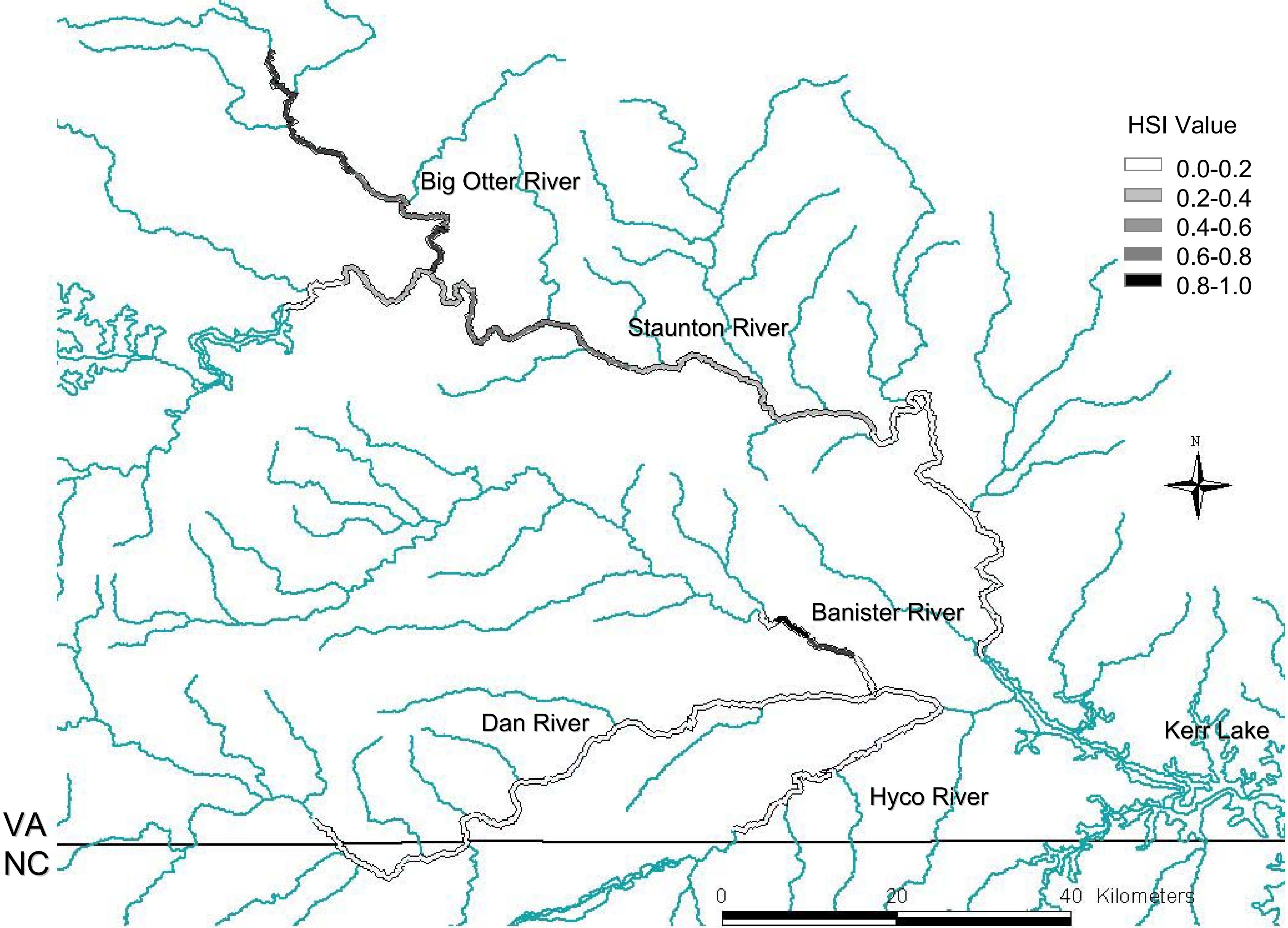
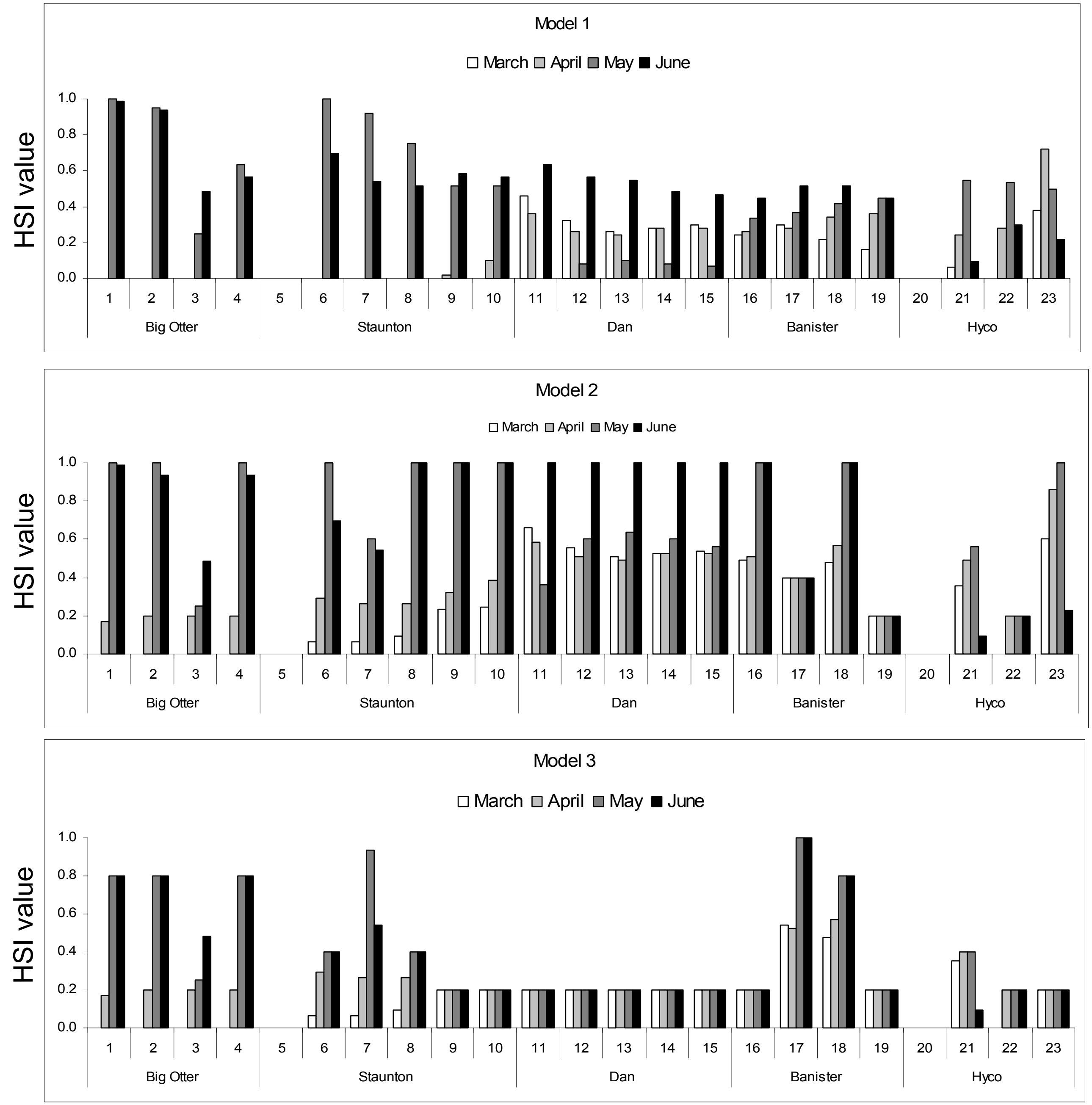


Figure 30. Comparison of HSI values among sites and months for the default Stier and Crance HSI and two alternative models with alternative suitability curves for water temperature and bottom substrate.



CHAPTER TWO

Hatching Success of American Shad Eggs in the Roanoke River Basin

INTRODUCTION

One approach that has been used effectively to test habitat quality is to evaluate egg hatching success through *in situ* incubation experiments (Kennedy 1980; Gunn and Keller 1984; Mohr et al. 1990; Waters 1998). For American shad, egg hatching experiments were conducted on the Susquehanna River as part of a restoration program (Carlson 1968). Fertilized eggs were placed in free-floating incubator boxes attached to a stationary object at various sites in the upper basin and monitored daily along with water quality (Bielo 1963). The availability of suitable environmental conditions for egg survival was a prerequisite for the reestablishment of runs on the Susquehanna River. To evaluate suitability of spawning habitat (in terms of water quality) for American shad in the Roanoke River basin, I conducted egg incubation experiments during the spring of 2004. The addition of a biological component to complement the habitat assessment observed in Chapter 1 provides further information about suitable release sites for spawning American shad in the Roanoke River basin.

METHODS

Eight of the ten incubation sites were chosen because they were close in proximity to USGS gaging stations and VADEQ water quality monitoring stations, as well as evenly spaced among the established monthly circuit sampling sites (Figure 1). I selected one site on the Big Otter River at Evington, three sites on the Staunton River at Altavista, Brookneal and Scuffletown Road; one site on the Banister River at Halifax; one site on the Hyco River at Denniston, and two sites on the Dan River at Danville and Paces. More sites were placed on the Dan and the Staunton rivers because they are considerably larger than the Big Otter, Banister, and Hyco rivers. Two additional sites were added downstream of Kerr Lake. The site immediately below Kerr Dam was added to examine water quality in the upper end of Lake Gaston below Kerr Dam. The egg incubation site below Roanoke Rapids Dam was added to evaluate the habitat that is the current upper limit to the American shad spawning migration. This is also reported to be the primary spawning area presently for American shad (Hightower and Sparks 2003).

Modified Plexiglas incubators (Figure 2) were used to estimate *in situ* hatching success of American shad eggs. The incubators consist of three Plexiglas plates, each with 50, 10-mm diameter holes. One egg is held in each of the 10-mm x 9-mm compartments. The incubators allow each egg to be exposed independently to the ambient water conditions while being protected from predation and possible spread of infection between eggs (Manny et al. 1989). These incubators have been successfully used in similar evaluations of hatching success with lake trout (Mohr et al. 1990), lake herring (Savino et al. 1994), and blueback herring (Waters 1998).

I also used Whitlock Vibert boxes (WVB) to estimate hatching success in the first and second pilot studies and the first field trial. These boxes have often been used in similar evaluations of salmonid hatching success through fry emergence (Barlaup and Moen 2001). WVBs are equipped with two perforated chambers, with the top chamber used to incubate eggs *in situ* before hatching and the lower chamber providing a protected space for the fry to emerge (Figure 3). Up to several hundred salmonid eggs can be held in the top chamber while experiencing most of the environmental factors that affect naturally spawned eggs (Whitlock 1977). American shad eggs (2.5-3.8 mm) (Walburg and Nichols 1967) are smaller in comparison to salmonid eggs (3.0-7.5 mm) (Whitlock 1977) that are normally used in the WVBs. Due to the small size of the American shad eggs, the WVBs were placed inside fine nylon mesh socks that conformed to the shape of the box, to prevent possible egg loss. The nylon mesh-covered boxes were then placed inside a larger mesh bag to facilitate attachment to a stationary object.

American shad used as brood stock were collected from the Cape Fear River by North Carolina Wildlife Resources Commission biologists. The fish were kept in well water at the Watha State Fish Hatchery in Watha, NC. To induce spawning, brood stock were given Luteinizing Hormone-Releasing Hormone

Implants (LHRHa) with a target dosage of 75 g/kg for females and 50 g/kg for males. Implants were injected intramuscularly just posterior and ventral to the dorsal fin. The fish spawned freely in 3.7-m diameter circular tanks and the resulting eggs were transferred to 7-L MacDonald hatching jars, where they were kept until hatching. The developing fertilized eggs were treated daily with a 1,667-ppm formalin standing bath with light aeration to prevent fungal growth, which could spread and cause egg mortality.

Two pilot studies were conducted at the Watha Hatchery to test the egg incubation apparatus (Table 1). In the first pilot experiment (April 2-7), eggs were loaded into six Plexiglas incubators and six WVBs, which were placed in a covered outdoor raceway. Newly fertilized eggs were used to ensure maximum exposure to ambient water. To test for the possible influence of egg density or fungal spreading in the WVBs, the six WVBs were loaded with 25, 50, or 100 eggs. In the second pilot study (April 5-8), the eggs were spawned and fertilized two days prior to loading into the incubators. This allowed us to examine whether there would be a difference in hatch rate based on developmental stage. Six Plexiglas incubators and six WVBs were placed in the same hatchery raceway as in the first pilot study but closer to the inflow pipe.

On the processing day, after incubation, each incubator was pulled out of the water and placed into a shallow tray filled with water to determine hatching results. Each developmental stage was recorded as a live egg, dead egg, dead fry or missing. Percent hatch was calculated using the following formula: (live egg + dead fry)/(total number of eggs). Live eggs were recorded as successful events because it was assumed those eggs would have hatched if the incubation period had been extended. Dead fry were included in the overall hatching percentage because the eggs successfully hatched. It was assumed that missing compartments contained dead eggs that had decomposed over the incubation period.

At each field site, four 3-m pieces of steel rebar were inserted securely into the substrate at the proper distance apart so the PVC pipe ends, attached to the incubators, would slide easily down the rebar. The rebar rods were placed at a depth so the incubators would be in approximately 0.5-m deep water and four 0.08-m pieces of PVC were situated onto the rebar first so that the incubators would not be flush with the bottom substrate (Figure 4). This was done to reduce the likelihood that eggs would be suffocated due to siltation. Two Plexiglas incubators were placed at each site (along with one WVB for field trial 1). The Plexiglas incubators were situated onto the rebar, and the WVB was placed inside a mesh bag that was then fastened to the rebar. I recorded time of deployment and several water quality parameters [dissolved oxygen (mg/L), temperature (ºC), conductivity (µS), turbidity (ntu), pH and current velocity (m/s)] daily for the duration of the incubation period.

At the end of the trial, the incubators were collected and placed in a cooler filled with 10% buffered formalin and taken back to the laboratory facility for processing. Each incubator was rinsed, placed into a shallow tray of water and disassembled. Incubator contents were recorded as a live egg, dead egg, or a dead fry. Hatching success was calculated using the same formula as in the pilot studies. The incubator contents were preserved in a small jar and labeled.

The first field trial was conducted on April 17-24, 2004 (Table 1). Eggs that had been fertilized on April 16th were loaded from the Watha State Fish Hatchery. Two Plexiglas incubators and one WVB for each site were loaded and placed into a large aerated cooler filled with water from the hatchery. WVBs were loaded with 100 eggs each. With ten sites and two sets of controls, a total of 24 Plexiglas incubators and 12 WVBs were used. One set of control incubators were placed at the hatchery and left for the duration of the trial and the other control set was transported along with the others to ensure there were no deleterious effects due to transport from the hatchery to field sites (Waters 1998). The transport controls were monitored for temperature and dissolved oxygen each morning and evening. The rebar rods and 0.08-m pieces of PVC were left at each site for the duration of the experiment to be used in each subsequent field trial.

Field trials 2 and 3 were conducted from April 30-May 5 and May 20-23, 2004. Because results from pilot study 2 were similar for incubators and WVBs, and to reduce the time required to load eggs for a trial, I discontinued use of the WVBs and placed only two Plexiglas incubators at each site. Otherwise, trials were done following the same protocol as for the first trial.

To compare percent hatch among sites, I used a two-way analysis of covariance with a block design. Trials were treated as blocks and locations were analyzed as treatments with water quality parameters included as covariates. Because our hatch values were percentages, we used an arcsin transformation of the percentage values (Snedecor and Cochran 1956). I used Pearson's correlation analysis (SAS Institute 1995) to assess relationships between arcsin-transformed percent hatch and the following water quality variables: water temperature, dissolved oxygen, conductivity, pH, turbidity and current velocity. Analysis of Variance was used to evaluate differences among rivers for each water quality variable.

RESULTS

For the first pilot study, percent hatch was 18.3% ± 31.2 in the Plexiglas incubators and 30.0% ± 30.5 in the WVBs (Figure 5). Overall average percent hatch for the first pilot study was 24.1% ± 31.4. For the second pilot study, mean percent hatch value was 93.6% ± 3.2 in the Plexiglas incubators and 72.4% ± 5.9 in the WVBs. Overall mean percent hatch for the second pilot study was 84.7% ± 11.6. The substantial increase in percent hatch from the first pilot study to the second pilot study (Figure 5) indicated that the experimental protocol used in the second pilot study (more time between fertilization and deployment and placing incubators closer to the source of flow) was effective. Water quality parameters remained relatively constant over the two trials with ranges of 17-18 C for water temperature, 6-9 mg/L for dissolved oxygen, 468-471 μS for conductivity, 0.2-0.3 ntu for turbidity, and 0.00-0.02 m/s for current velocity, with pH constant at 7.8.

My primary focus for this study was to compare sites based upon the percent hatch of eggs as related to overall water quality differences. Water temperature, and hence the rate of egg development, varied among sites and trials. The length of a trial ranged from 3 to 5 days (Table 2) and was varied based on temperatures at incubation sites. The differences in temperature among sites resulted in some sites having larger numbers of live eggs (e.g. Kerr Dam) while others (e.g. Danville) had larger proportions of dead fry (Figure 6). Figure 7 shows the stages of development at 17 C.

For the first field trial, percent hatch at field sites averaged 88.4% ± 10.1 from Plexiglas incubators and 48.2% ± 26.1 from WVBs. Percent hatch in Plexiglas incubators was also higher than in WVBs for the Watha hatchery controls (91.0 vs. 75.0%) and transport controls (86.0 vs. 5.0%). Given the consistently better results from the Plexiglas incubators, I discontinued use of the WVBs. Subsequent results are restricted to Plexiglas incubators only.

Percent hatch from trial 1 averaged 88.4% ± 10.1 for field sites compared to 91.0% ± 7.0 for hatchery controls and 86.0% ± 12.0 for transport controls (Table 3, Figure 8). For the second trial, mean percent hatch was 91.3% ± 8.4 for field sites compared to 97.0% ± 3.0 for hatchery controls and 88.0% ± 4.0 for transport controls (Table 3, Figure 8). For field trial 3, mean percent hatch decreased to 76.7% ± 17.0 compared to 96.0% ± 2.0 for hatchery controls and 84.0% ± 2.0 for transport controls (Table 3, Figure 8). The lowest percent hatch in trial 3 was at Roanoke Rapids (37.0%). Eight of the ten field sites had lower values for trial 3 than for trials 1 and 2.

For dissolved oxygen, there was a significant difference among trials ($p<0.0001$) (means of 9.3, 8.0, and 7.1 mg/L for trials 1-3) but not among sites ($p=0.17$) (Figure 9). Temperature differed significantly among trials ($p<0.0001$) (means of 16.4, 17.0, and 23.5 C for trials 1-3) and sites ($p<0.0001$) (Figure 9). Average temperatures were lowest for Altavista (13.3 C) and Kerr Dam (13.4 C) sites. The differences in temperature likely account for the consistent differences among sites and trials in the proportion of eggs at different developmental stages (Figure 6). They are also consistent with the gradually decreasing percent hatch from trial 1 to trial 3.

Conductivities were marginally different ($p=0.09$) among trials but significantly different among locations ($p<0.0001$). Mean conductivities were highest at the Altavista (147.2 μS) and Danville (135.3 μS) sites and lowest at the Big Otter (68.7 μS) and Banister (66.6 μS) sites. There were significant turbidity differences among locations ($p=0.01$) and trials ($p=0.01$) with the highest mean turbidities during the third trial (35.2 ntu). The Roanoke Rapids site had the lowest mean turbidity (2.9 ntu) and the Banister River site had the highest mean turbidity (39.0 ntu). There was a marginal difference among locations ($p=0.07$) for mean pH, and mean pH was significantly higher during trial 2 (7.6) compared to the other two trials ($p<0.0001$). Mean current velocities were significantly ($p=0.02$) higher during the third trial (0.19 m/s) compared to the other trials ($p=0.02$). The Hyco River site had significantly higher mean current velocities (0.35 m/s) than the other incubation sites ($p<0.0001$).

I found significant correlations (Table 4) between percent hatch and two water quality variables: temperature ($r= -0.54$; $p=0.002$) and dissolved oxygen ($r= 0.51$; $p=0.004$). There was a consistent pattern of increasing temperature and decreasing dissolved oxygen levels over the three field trials (Figure 9) and the lowest percent hatch values generally occurred in the third trial (Figure 8).

An analysis of covariance, that included all water quality parameters as covariates, indicated that dissolved oxygen had a significant linear effect on percent hatch (Table 5). A reduced model with only dissolved oxygen as a covariate indicated that trial and dissolved oxygen were significant effects, with a marginal ($p=0.062$) effect for location.

DISCUSSION

Results from the pilot studies established that Plexiglas incubators and WVBs could be used to evaluate hatching success for American shad eggs. These types of incubators had not been used previously in incubation experiments with American shad, but the Plexiglas incubators had been used with blueback herring in a coastal North Carolina river (Waters 1998) and WVBs have been widely used in salmonid incubation experiments (Barlaup and Moen 2001).

The Plexiglas incubators were easy to load and process and were very durable. The WVBs were more difficult to use because the perforations inside the WVBs were designed for salmonid eggs and fry and were too large to retain American shad eggs or fry. Enclosing the WVBs in a nylon mesh sock retained the eggs and fry but made processing very difficult. There was also more fungal growth observed in the WVBs than in the Plexiglas incubators, which may have been due to fungus spreading between individual eggs. Another concern was that American shad eggs and fry are delicate and can easily break when touched, so it is possible that when eggs adhered to the nylon mesh, they were damaged and began to deteriorate. Had the perforated holes been smaller and customized for use with American shad, a box such as the WVB would presumably work well.

Originally we planned to use eggs as recently fertilized as possible, so as to maximize the amount of time the eggs spent developing at each site. For the first pilot study, I used eggs that had been spawned within the past 8 to 14 hours. The exact hour of fertilization is not known, but it is estimated that spawning and fertilization began at 20:00 and ended at 06:00 the following morning. At this stage of development, the difference between dead eggs and developing eggs can be difficult to discern even under magnification. Massmann (1952) classified an egg as dead if the yolk had coagulated or had adhered to the vitellin membrane. Since dead eggs were visibly opaque, I loaded eggs that were not opaque, but it would be difficult to discern whether or not the yolk had adhered to the vitellin membrane. This may have been one of the factors resulting in the low percent hatch value in the first pilot study.

Other potential factors contributing to low percent hatch in the first pilot study were placement of the incubators within the raceway, inexperienced loading technique, and low survival from the source batch of eggs. Positioning the incubators at the bottom of a 0.9-m deep raceway, with little flow, might have caused the eggs to experience localized oxygen depletion inside their incubators. Eggs that are incubating need a constant supply of dissolved oxygen, and are rarely found in waters with less than 5 mg/L (Marcy 1972, Ross et al. 1993a).

The two main changes made from the first pilot study to the second were moving the incubators closer to turbulent water at the inflow pipe in the raceway and use of eggs that had been fertilized two days prior and survived a routine daily formalin dip. For the second pilot study, I used eggs that had been fertilized 56 to 74 hours previously. At this stage of development, dead eggs are an obvious opaque white and the live developing eggs are larger and clear with a yellowish developing embryo contained inside. A small amount of movement inside the embryo can also be observed. On the first day after fertilization, the eggs are dipped in a 1,667-ppm formalin standing bath to kill any fungal growth. If developing eggs are able to withstand the formalin dip, it is an indicator of good egg health (J. Evans, NC Wildlife Resources Commission personal communication).

For the field trials, there was not a statistically significant difference in percent hatch among sites. Sites generally had similar values for percent hatch except for the potentially anomalous value for Roanoke Rapids in trial 3. If the Roanoke Rapids site is excluded and the reduced model is rerun, the p-value for the location effect increases to 0.28 from 0.06.

Each river appears to be suitable for stocking fry or release of adults, based on this short-term measure of water quality. The lowest percent hatch (37.0%; average of 50% and 24%) was from the third trial at the Roanoke Rapids site, which is reported to be the primary current spawning grounds for American shad (Hightower and Sparks 2003). The next lowest percent hatch value was from the Banister site, with 78% hatch success. The remaining sites had relatively high percent hatch levels with three sites (Altavista, Kerr Dam, and Danville) at or above 90% for all three trials.

There was a significant difference in percent hatch among trials, which was expected because water quality parameters changed temporally. Temperatures during the first trial were as low as 12 C at some sites, which is 2-2.5 degrees lower than the optimal ranges proposed for American shad (Stier and Crance 1985; Bilkovic et al. 2002). Marcy (1972) suggested that American shad eggs developing at low temperatures, <16°C, could experience higher mortality rates because of prolonged development. Our results, however, do not suggest a decrease in percent hatch at temperatures below 16°C. The second trial yielded a slightly higher mean percent hatch value (91.3%) compared to trial one (88.4%). Temperatures during trial two were within the optimal range proposed by Bilkovic et al. (2002) of 14.5 C to 24.5 C for egg and larval development. Only three of ten sites during trial two had a mean temperature of less than 16 C and all were below 20 C. Our technique may have also improved in terms of recognizing healthy developing eggs for loading into incubators during this second trial.

I reduced the incubation time for trial 3 to only three days, because the higher temperatures hastened the development process. Percent hatch decreased in the third trial to 76.7%. The average temperature across all sites had increased to a mean value of 23.5 C, which is within the optimal range proposed by Bilkovic et al. (2002) but above the optimal range defined by Stier and Crance (1985). Massmann (1952) observed that hatching took place in three days at temperatures of 23.3 C. It is also possible that percent hatch could be underestimated if some of the eggs hatched and then died and deteriorated because of the relatively high temperatures.

The results of my study suggest that dissolved oxygen level can have an important effect on the success of an American shad restoration program. Based on my analysis of covariance, dissolved oxygen was the most important water quality variable affecting percent hatch, even though the mean dissolved oxygen level was above the recommended minimum of 5 mg/L (Stier and Crance 1985; Chittenden 1973; Bilkovic et al. 2002) for all sites and trials. The mean dissolved oxygen level across all trials was 7.9 mg/L, and dissolved oxygen measurements never dropped below 6.1 mg/L, but did steadily decrease from the first trial to the third. Temperature may also have played a role, although it is difficult to separate the effects of temperature and dissolved oxygen because of the correlation between those variables.

Several current velocities measured at the incubator sites (0.06-0.61 m/s; mean of 0.14 m/s) were lower than the optimal range defined in the habitat suitability model for spawning American shad (0.30 m/s to 0.91 m/s; Stier and Crance 1985). Hatch rates may have been high despite the relatively low current velocities because the eggs were suspended off-bottom and would be less subject to siltation. Bilkovic et al. (2002) suggested an optimal range of 0.3-0.7 m/s for egg and larval stages of American shad. Ross et al. (1993a), in their field test of the Stier and Crance (1985) HSI model, observed velocities between 0.0-0.7 m/s in the Delaware River, suggesting the lower limit for current velocity could possibly be decreased from 0.3 m/s to 0 m/s. Leim (1924) reported current velocities (m/s) between 0.3 and 0.9 in the Connecticut River, MA during egg collections. It is generally accepted that American shad spawning occurs in shallow waters with high dissolved oxygen and fast currents (Walburg and Nichols 1967; Carlson 1968). It has been suggested that these conditions may enhance mixing of eggs and sperm as well as prevent siltation and suffocation of newly fertilized eggs (Bilkovic et al. 2002).

Turbidity level was not correlated with percent hatch even though it ranged widely over the three trials (3.6-129 ntu; mean of 25.1 ntu). In a study conducted by Ross et al. (1993b) in the Delaware River, American shad eggs were not found in turbidities greater than 2.7 ntu. However, Walburg and Nichols (1967) report that conditions on spawning grounds can range from clear to very turbid. In a study by Leim (1924), American shad were found in waters that were "very muddy and usually extremely turbid." Leim also found that prolonged exposure to suspended sediments of 1,000 mg/L did not have a negative affect on egg survival, but did negatively effect larval survival. Turbidity may have had less of an effect in our experiment because the eggs were not in direct contact with the substrate and because I did not evaluate larval survival.

Values for pH were relatively stable with a range of 7.2 to 7.8 and a mean value of 7.4 ± 0.2. The reported optimal suitability range for pH is between 6.0 and 9.9 (Stier and Crance 1985; Bilkovic et al. 2002), and it has been reported that American shad adults, eggs, and larvae can tolerate a wide pH range even at variable temperatures (Leim 1924). Thus, our results suggest that pH is not a limiting factor for restoration of American shad in this system.

Results of this study demonstrate that water quality is adequate to allow for successful hatching of American shad eggs in the Roanoke River basin. A worthwhile extension would be to examine whether hatching rate would be substantially different for eggs in contact with the substrate. That could increase the importance of other habitat characteristics such as current velocity, turbidity, and substrate type. It would also be worthwhile to conduct studies of fry growth and survival within the different river systems. The approach that I used provides little information about fry because the fry do not generally survive for long periods in the small spaces in the Plexiglas incubators. Another useful extension would be to examine contaminant concentrations and their effects on egg hatching success and (longer-term) larval growth and survival.

Table 1. Summary of methods used during field season of 2004 to estimate percent hatch for American shad eggs in the Roanoke River Basin.

	Hatchery Pilot #1	Hatchery Pilot #2	Trial #1	Trial #2	Trial #3
Time of Approximate Spawn and Fertilization	between 4/2/2004 20:00 and 4/3/2004 06:00	between 4/2/2004 20:00 and 4/3/2004 06:00	between 4/15/2004 20:00 and 4/16/2004 04:00	between 4/29/2004 00:00 and 4/29/2004 06:00	between 5/17/2004 21:00 and 5/18/2004 06:00
Time of first formalin dip at Watha State Fish Hatchery	4/2/2004 13:00	4/4/2004 13:00	4/16/2004 16:30	4/29/2004 16:00	5/19/2004 17:00
Batch survival estimate as calculated by Watha State Fish Hatchery	0%	0%	52%	47%	24%
Number of Brood stock used in fertilization	27 males/15 females	27 males/15 females	52 males/27 females	58 males/39 females	25 males/46 females
Date incubators loaded	4/2/2004	4/5/2004	4/17/2004	4/30/2004	5/20/2004
Length of Time to load incubators	2.5 hours	2 hours	4 hours	2 hours	2 hours
Number of incubators loaded	12	12	36	24	24
Time of First Deployment	4/2/2004 12:41	4/5/2004 18:15	4/17/2004 15:02	5/1/2004 7:24	5/21/2004 8:50
Time of Last Deployment	4/2/2004 12:41	4/5/2004 18:15	4/18/2004 18:30	5/1/2004 18:14	5/21/2004 19:45
Length of time between fertilization and deployment	4-9 hours	60-70 hours	35-70 hours	55-60 hours	75-95 hours
Length of time exposed to site specific water	118-123 hours	64-68 hours	75-94 hours	92-96 hours	37-56 hours
Mean incubation length	121 hours	66 hours	85 hours	94 hours	47 hours
Mean % hatch	24.14%	83.00%	75.00%	91.50%	77.40%

Table 2. Deployment time, retrieval time, and length of deployment for pilot and field trials by site

	Hatchery Pilot #1			Hatchery Pilot #2			Trial #1			Trial #2			Trial #3		
	Deployed	Retrieved	Length of Deployment (hrs)	Deployed	Retrieved	Length of Deployment (hrs)	Deployed	Retrieved	Length of Deployment (hrs)	Deployed	Retrieved	Length of Deployment (hrs)	Deployed	Retrieved	Length of Deployment (hrs)
Hatchery Control	4/2 12:00	4/7 14:00	121.6	4/5 11:00	4/8 13:00	74.0	4/17 10:56	4/21 10:00	95.0	4/30 15:47	5/5 7:00	111.0	5/20 16:29	5/24 8:00	87.5
Transport Control							4/17 10:56	4/21 10:58	96.0	4/30 15:47	5/5 5:04	109.0	5/20 16:29	5/23 5:38	61.0
Roanoke Rapids							4/17 15:02	4/21 13:37	94.4	5/1 7:24	5/5 14:28	103.0	5/21 8:50	5/23 7:23	47.0
Kerr Dam							4/17 17:10	4/21 15:01	94.0	5/1 8:47	5/5 13:19	100.5	5/21 10:13	5/23 8:48	46.5
Hyco River at Rt. 744							4/18 15:40	4/21 16:10	72.3	5/1 10:07	5/5 12:04	98.0	5/21 11:25	5/23 10:14	47.0
Dan River at Paces							4/18 16:53	4/21 17:30	72.3	5/1 12:20	5/5 11:22	95.0	5/21 13:25	5/23 12:18	46.8
Dan River at Danville							4/18 18:30	4/21 18:02	71.5	5/1 13:50	5/5 6:46	89.0	5/21 12:36	5/23 11:22	47.0
Banister River at Rt. 614							4/18 13:40	4/21 17:10	75.6	5/1 11:19	5/5 10:44	95.6	5/21 14:07	5/23 13:31	47.5
Big Otter River at Evington							4/18 8:44	4/21 19:32	82.8	5/1 17:30	5/5 8:37	87.0	5/21 16:30	5/23 16:04	47.5
Staunton at Altavista							4/18 8:04	4/21 19:09	82.0	5/1 18:14	5/5 7:59	86.0	5/21 19:45	5/23 16:45	45.0
Staunton at Brookneal							4/18 10:29	4/21 20:21	81.6	5/1 16:27	5/5 9:22	88.7	5/21 15:43	5/23 15:15	47.5
Staunton at Scuffletown Rd							4/18 11:45	4/21 21:18	81.4	5/1 15:17	5/5 10:13	91.0	5/21 14:47	5/23 14:12	47.5
Mean Length of Deployment			121.6			74.0			83.2			96.2			51.5

Table 3. Percent hatch and mean water quality parameter values for locations and trials

Percent Hatch and Water Quality Parameters	Trial #	Location									
		Big Otter	Altavista	Brookneal	Scuffletown	Kerr Dam	Roanoke Rapids	Banister	Danville	Paces	Hyco
Percent Hatch	trial #1	68	96	88	86	91	85	95	93.9	86	95
	trial #2	94	94	95	99	98	85	74	96	91	87
	trial #3	79	91	82	69	90	37	65	90	91	73
Dissolved Oxygen (mg/L)	trial #1	8.33	9.97	9.20	8.29	10.09	9.80	11.51	8.73	8.64	8.44
	trial #2	8.40	8.98	8.55	7.10	8.04	8.01	7.24	8.62	7.80	7.35
	trial #3	7.37	7.87	8.11	6.35	7.99	6.47	6.36	7.54	6.76	6.54
Temperature (°C)	trial #1	16.0	12.4	14.3	15.5	13.5	19.2	18.3	18.2	17.7	19.1
	trial #2	15.8	14.5	16.1	17.4	15.3	19.7	17.3	17.8	17.7	18.2
	trial #3	23.0	20.6	24.3	24.9	19.0	24.7	24.1	24.9	25.2	24.0
Conductivity (µS)	trial #1	67.00	146.23	131.53	126.70	103.77	101.60	69.20	142.60	92.27	108.90
	trial #2	74.23	160.28	141.38	129.38	103.43	108.80	73.15	161.13	111.38	119.45
	trial #3	82.97	153.00	137.37	127.03	104.50	120.40	75.53	120.13	108.27	147.70
Turbidity (ntu)	trial #1	24.2	22.8	26.7	31.7	7.0	11.7	23.7	21.2	28.7	15.4
	trial #2	14.7	9.3	15.3	16.1	14.6	5.7	48.3	21.5	42.0	15.4
	trial #3	25.2	52.7	38.3	21.9	24.2	4.1	58.0	62.6	54.8	10.2
pH	trial #1	7.32	7.28	7.49	7.40	7.37	7.61	7.37	7.19	7.22	7.15
	trial #2	7.62	7.65	7.75	7.81	7.33	7.57	7.58	7.49	7.55	7.28
	trial #3	7.33	7.33	7.17	7.17	7.17	7.33	7.33	7.17	7.17	7.20
Current Velocity (m/s)	trial #1	0.12	0.18	0.04	0.04	0.11	0.04	0.07	0.05	0.23	0.28
	trial #2	0.09	0.14	0.01	0.03	0.02	0.00	0.04	0.16	0.30	0.34
	trial #3	0.24	0.06	0.23	0.04	0.06	0.04	0.08	0.29	0.37	0.51

Table 4. Simple correlations (r) between dissolved oxygen, temperature, conductivity, pH, current velocity, and the arcsin of percent hatch

	Mean[DO (mg/L)]	Mean[temp (°C)]	Mean[cond (µS)]	Mean[turb (ntu)]	Mean(pH)	Mean[current (m/sec)]
Mean[DO (mg/L)]						
Mean[temp (°C)]	**-0.66**					
Mean[cond (µS)]	-0.04	-0.03				
Mean[turb (ntu)]	-0.29	**0.38**	-0.15			
Mean(pH)	0.18	**-0.47**	0.02	-0.28		
Mean[current (m/sec)]	-0.25	**0.36**	0.12	0.21	**-0.46**	
Arcsin(% hatch)	**0.51**	**-0.54**	0.26	-0.07	0.27	-0.04

Table 5. Summary of Full vs. Reduced Analysis of Covariance Models, the Full Model included all water quality parameters, the Reduced Model included dissolved oxygen only as a covariate. Trials are used as blocks and Locations are used as treatments

Full Model					
Source of Variation	df	SS	MS	F	p-value
Trials	2	0.072	0.036	1.743	0.217
Locations	9	0.361	0.040	1.934	0.142
Dissolved Oxygen (mg/L)	1	0.154	0.154	7.446	**0.018**
Temperature (°C)	1	0.031	0.031	1.477	0.248
Conductivity (µS)	1	0.002	0.002	0.108	0.748
Turbididty (ntu)	1	0.016	0.016	0.781	0.394
pH	1	0.040	0.040	1.912	0.192
Current Velocity (m/s)	1	0.017	0.017	0.829	0.381
Error	12	0.249	0.021		
Total	29				

Reduced Model					
Source of Variation	df	SS	MS	F	p-value
Trials	2	0.282	0.141	6.461	**0.008**
Locations	9	0.460	0.051	2.348	**0.062**
Dissolved Oxygen (mg/L)	1	0.205	0.205	9.426	**0.007**
Error	17	0.370	0.022		
Total	29				

Figure 1. Roanoke River Basin study area with egg incubation sites, dam locations, USGS Gaging stations and VADEQ monitoring stations shown.

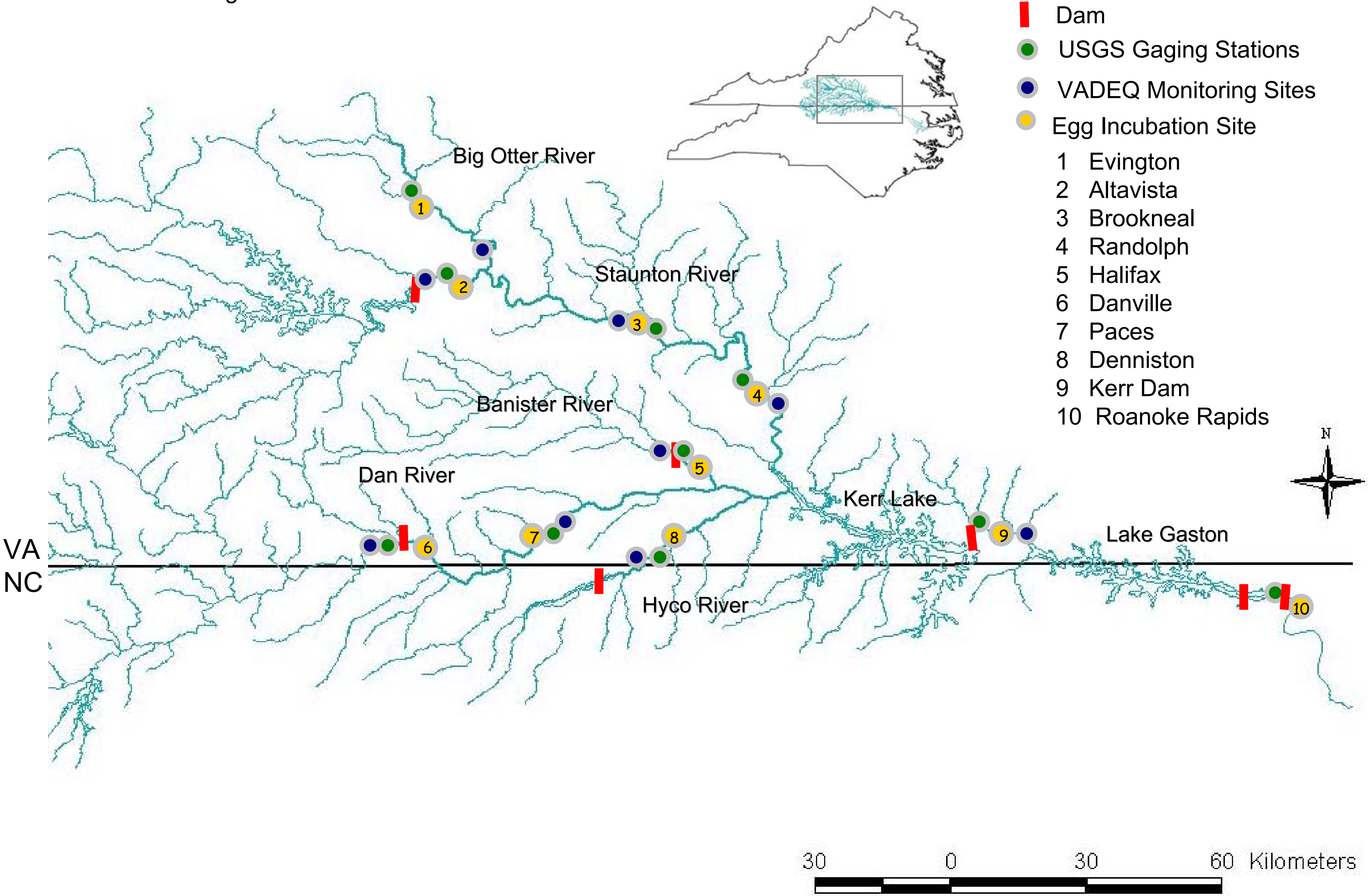


Figure 2. Diagram of Plexiglas incubator used in determining hatching success of American shad eggs (Modified from drawing in Evans et al. 1994).

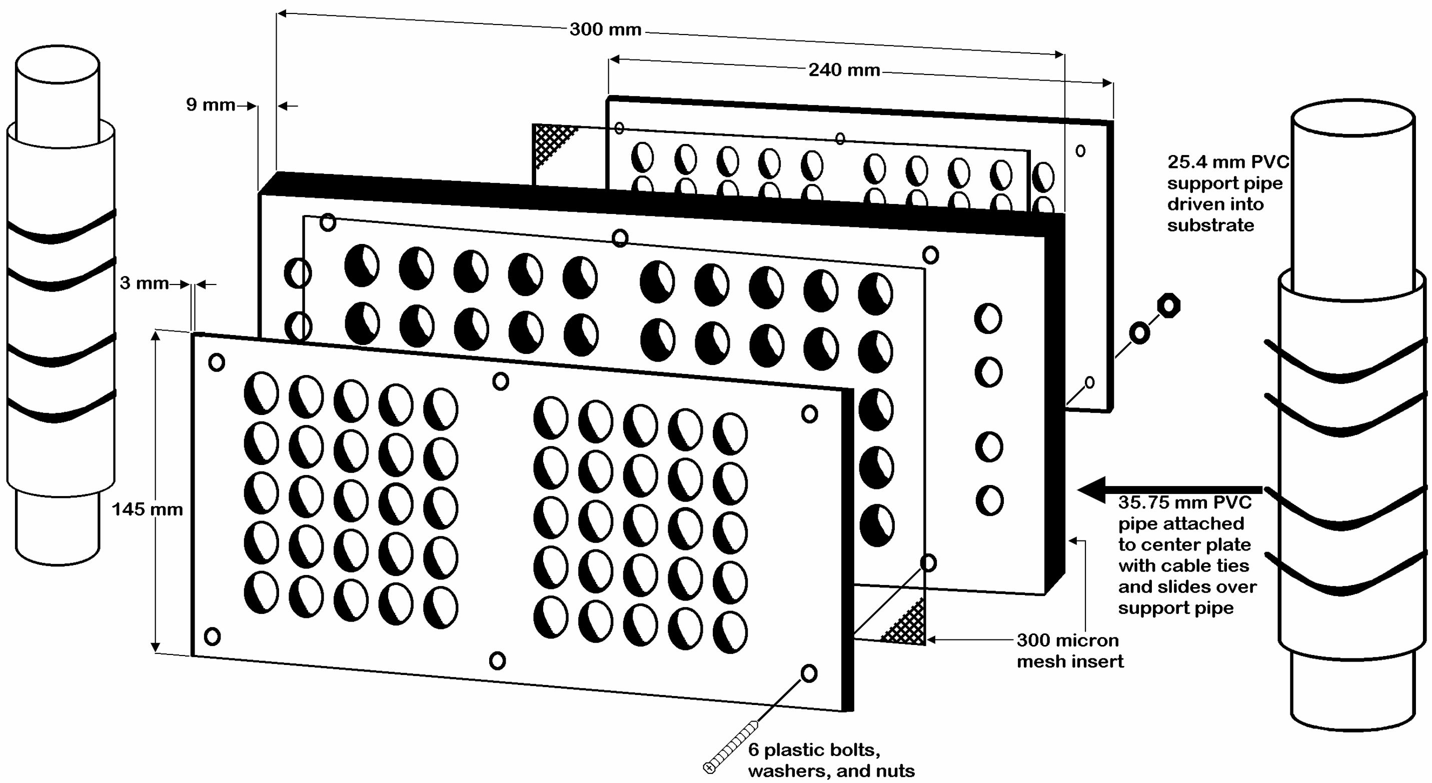


Figure 3. Diagram of Whitlock Vibert Box used in determining *in situ* hatching success and fry emergence. (www.fedflyfishers.org)

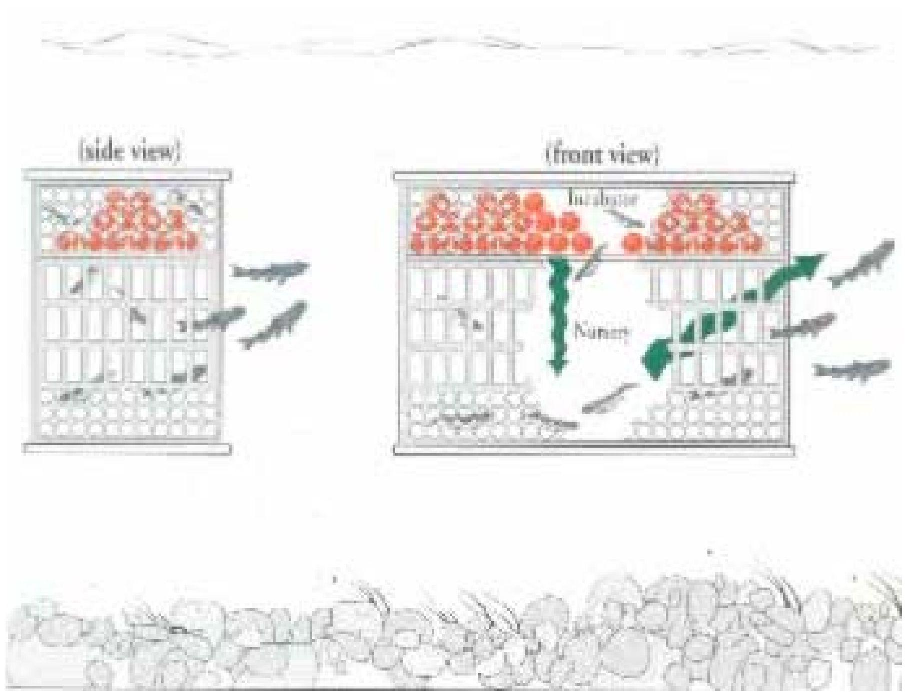


Figure 4. Incubators set up at each incubation site.

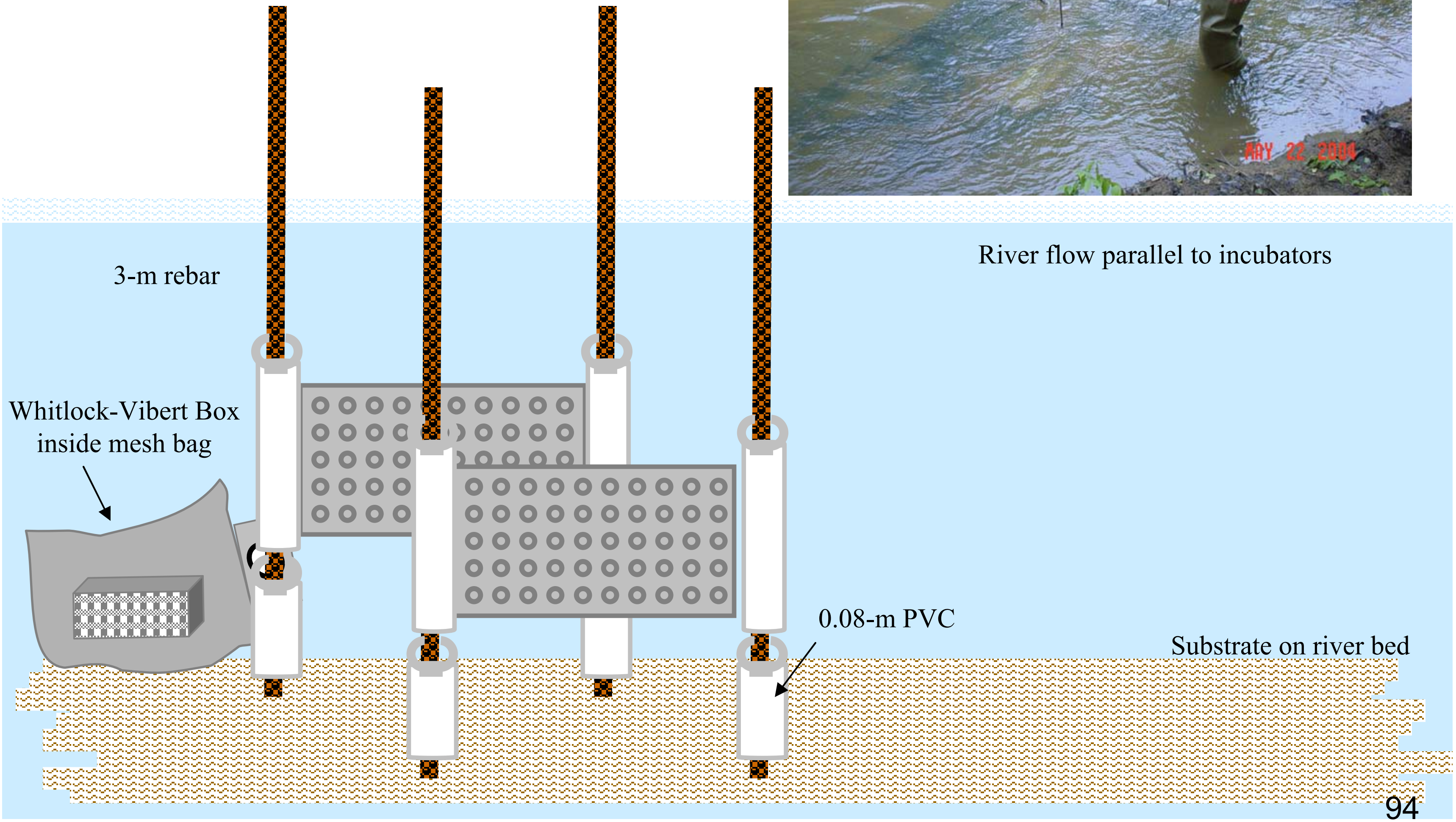


Figure 5. Percent hatch for Pilot Studies 1 and 2 conducted at the Watha hatchery. Plexiglas and Whitlock Vibert Boxes (WVB) were placed in a concrete raceway for the duration of each trial. The time from fertilization to deployment and placement of incubators were changed from pilot #1 to pilot #2. The number of eggs per WVB varied from 25-100.

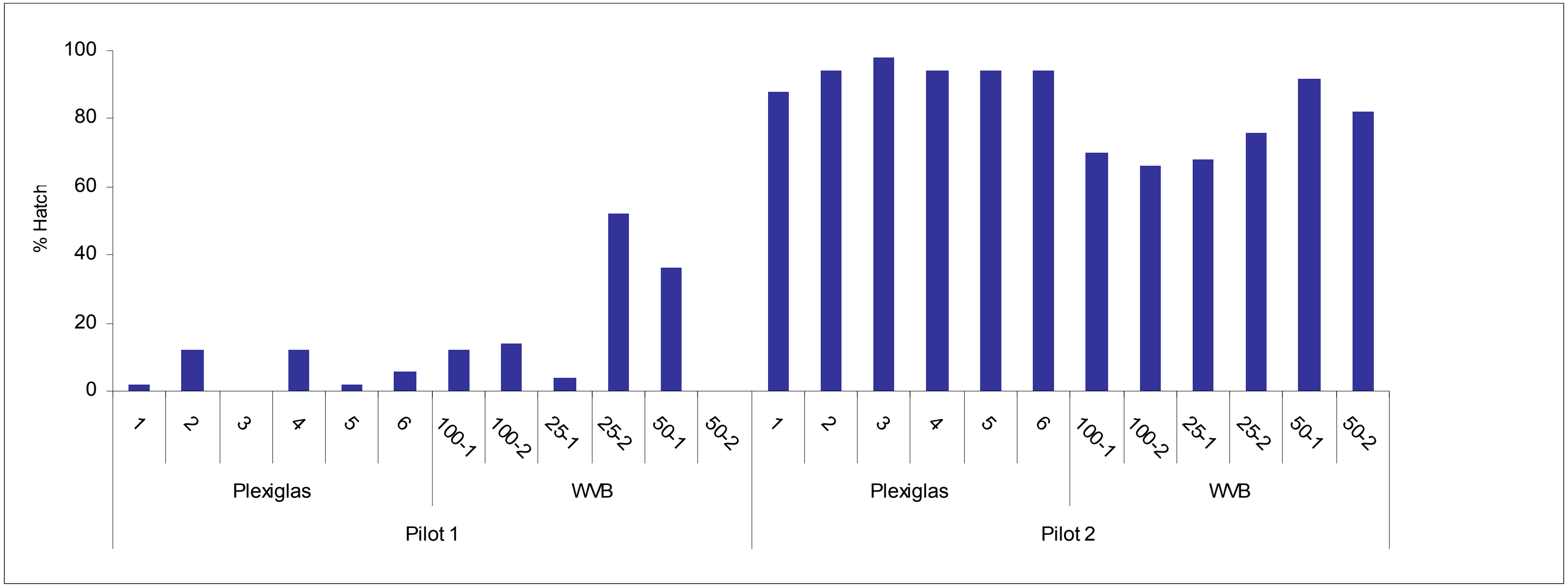
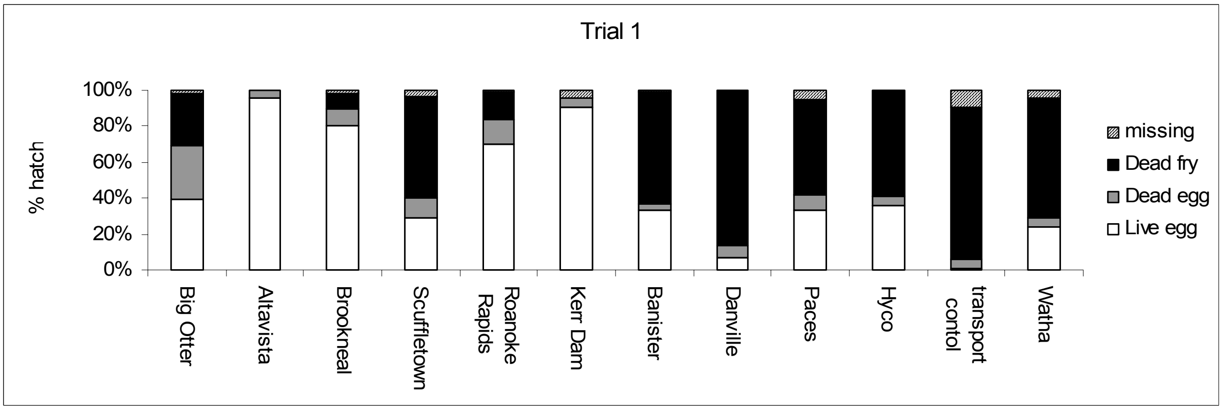
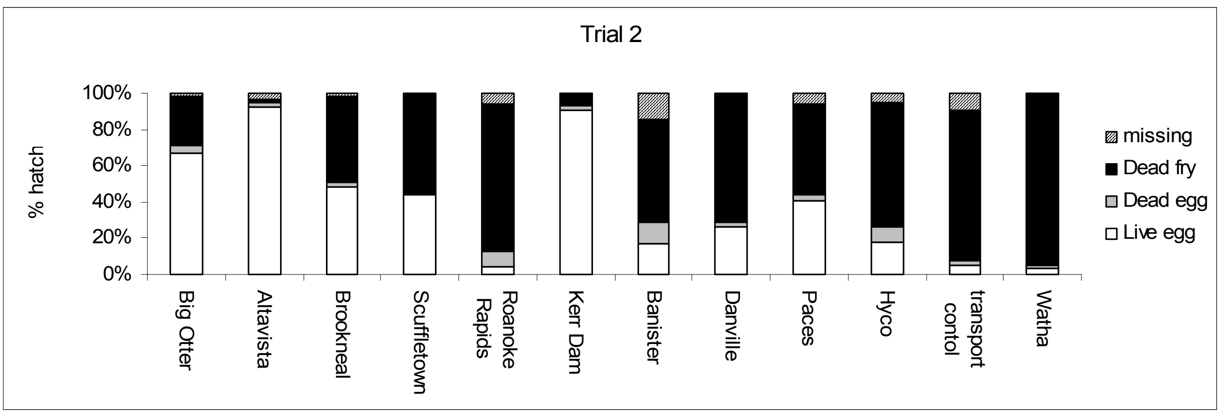


Figure 6. Proportions of different developmental stages at different incubation sites and trials





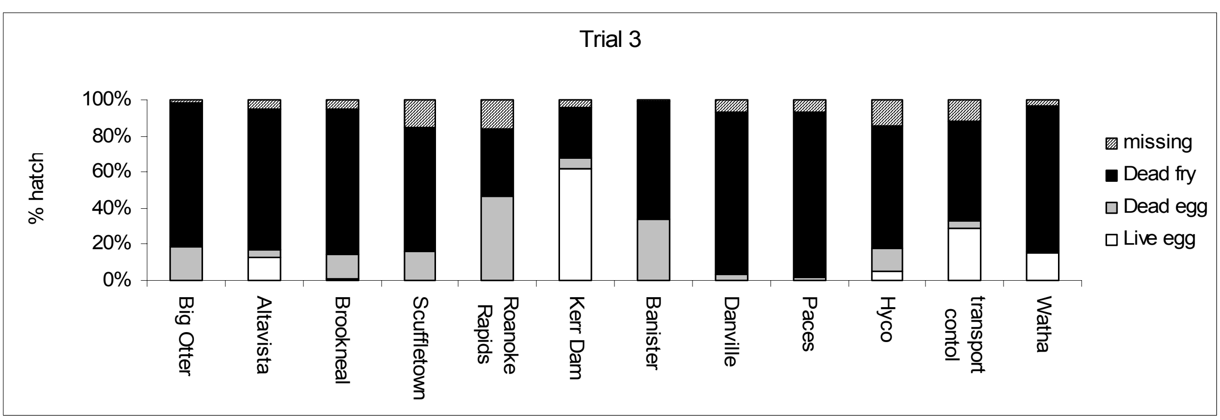


Figure 7. Daily developmental stages of fertilized American shad eggs at 17°C

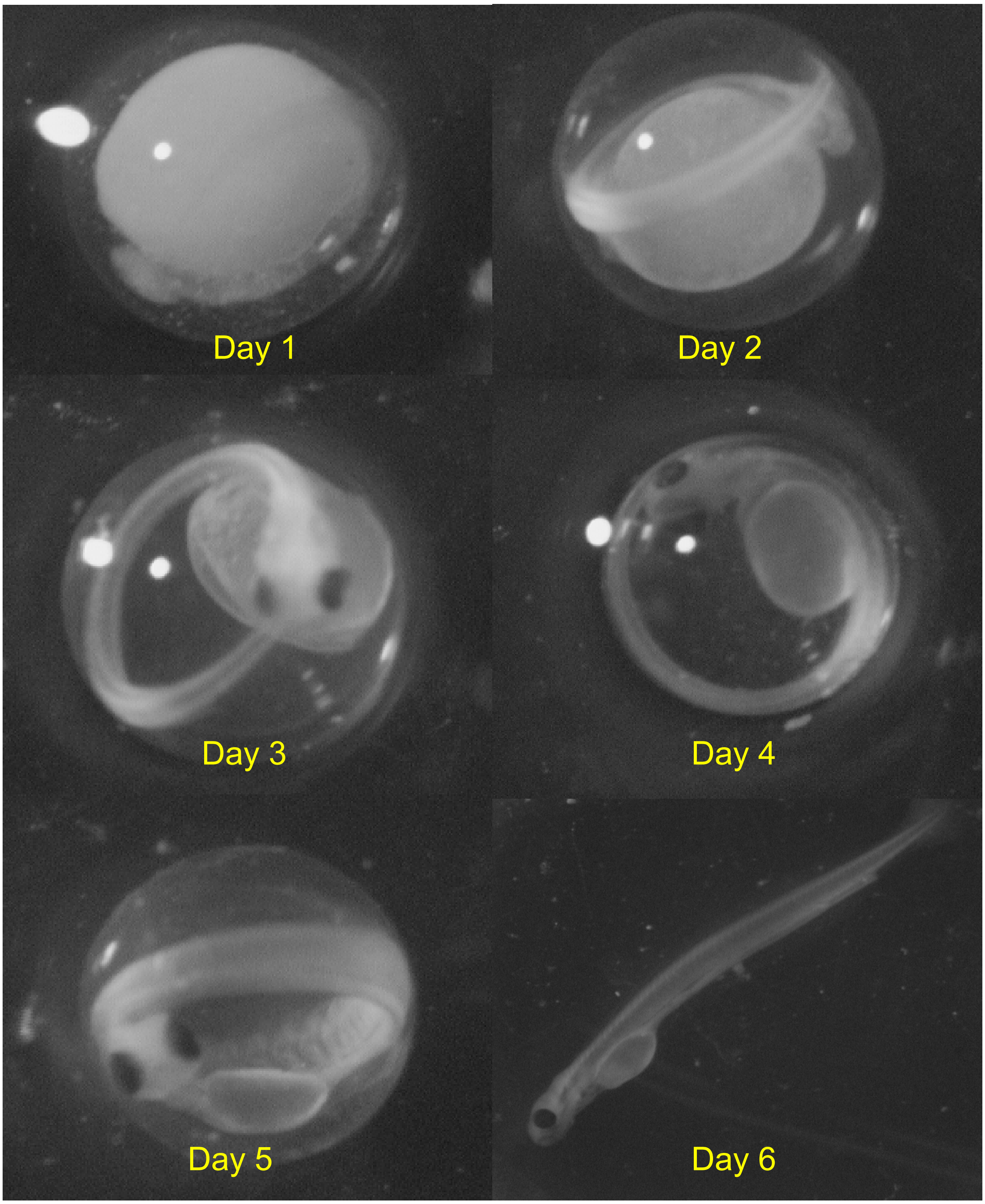


Figure 8. Percent hatch values by incubation site and trial.

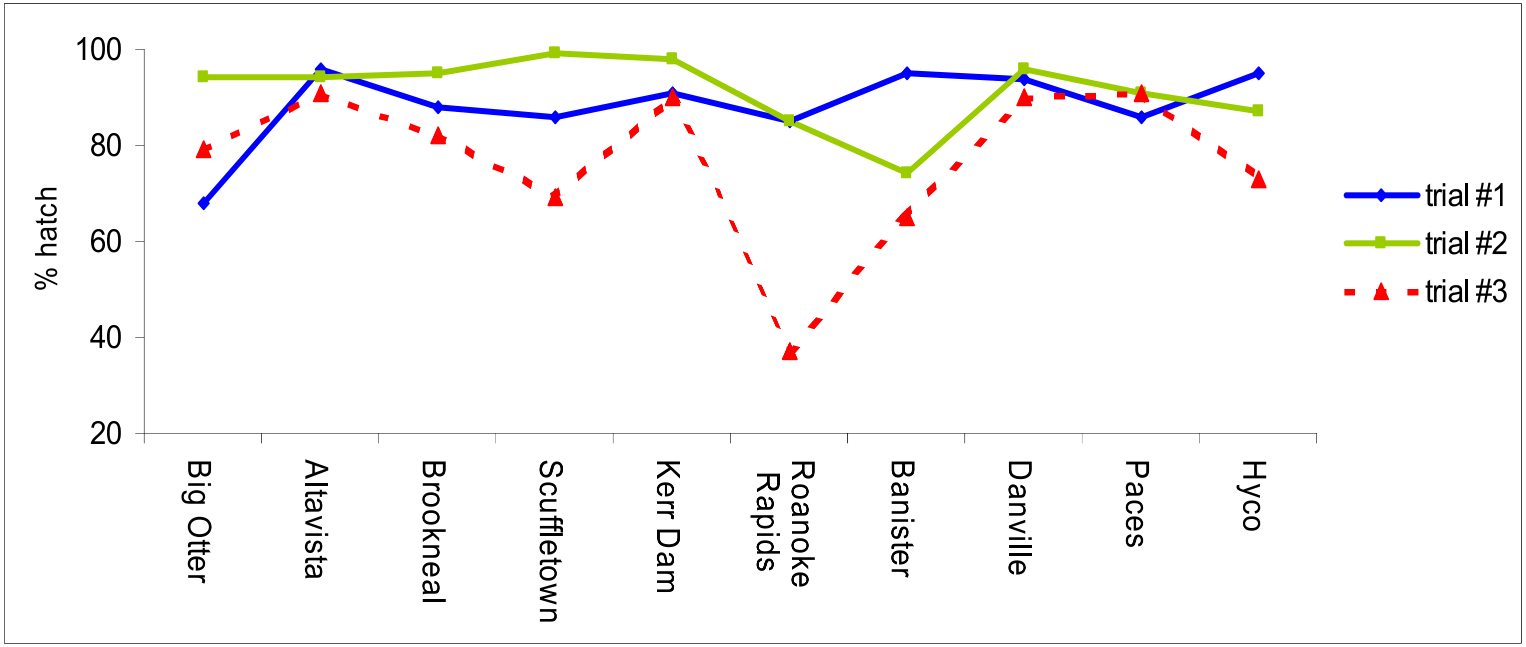
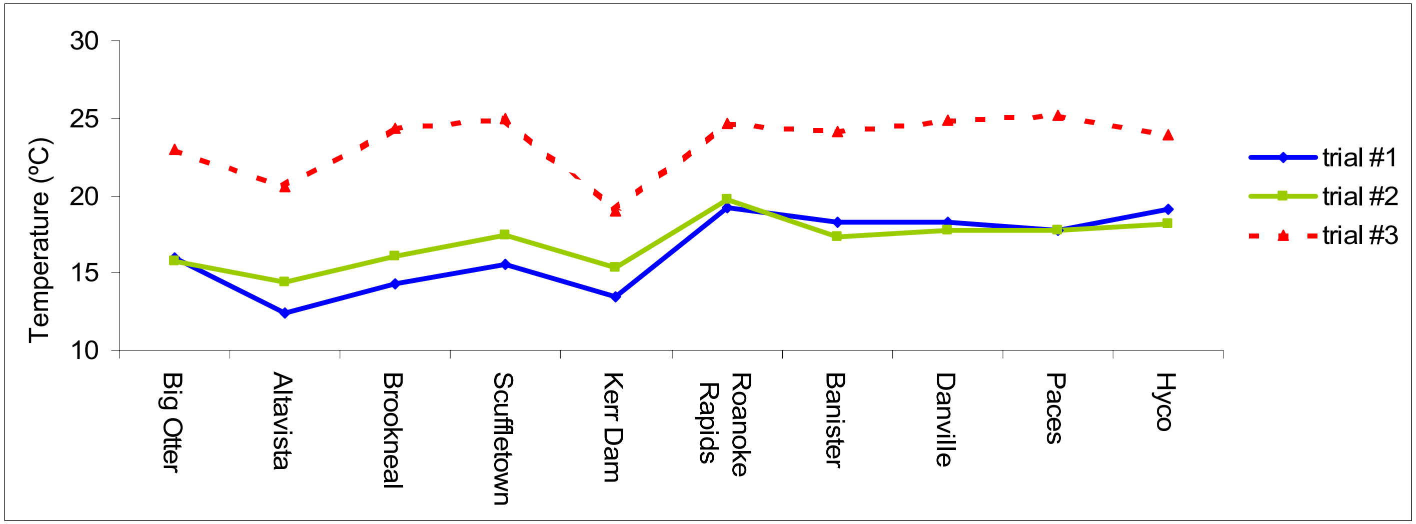
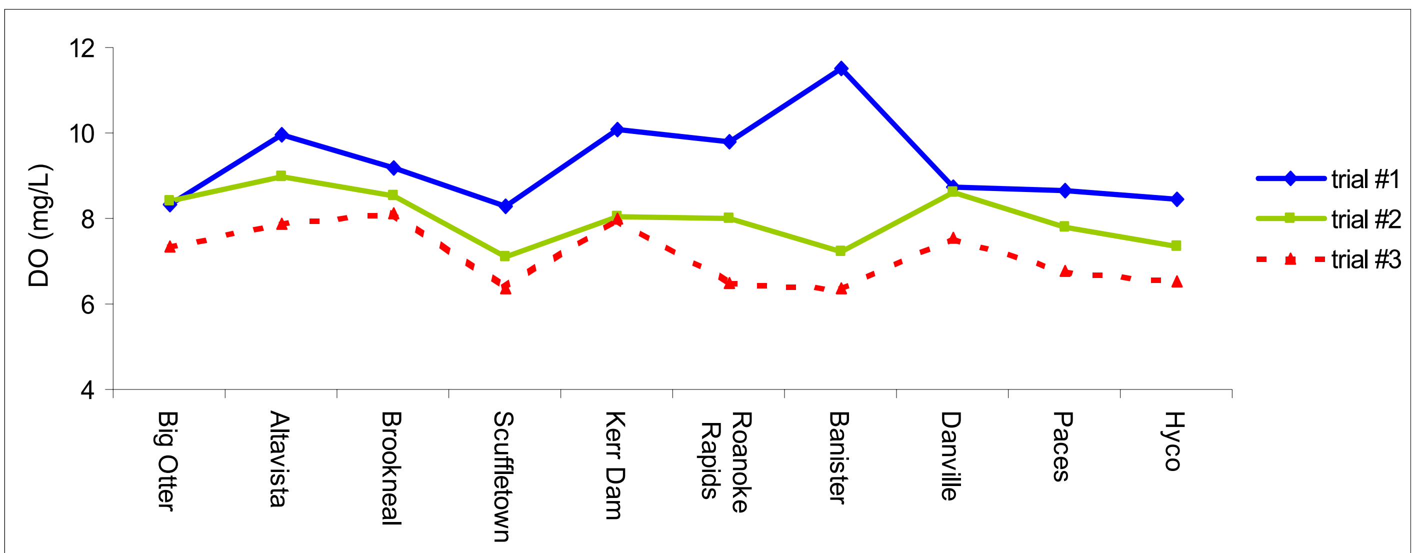


Figure 9. Mean temperature and dissolved oxygen values by incubation site and trial





CONCLUSION

Results from this research suggest that a program to trap and transport American shad into the Roanoke basin above Kerr Reservoir will be successful. The physical habitat assessment and results of HSI modeling indicate that there is a considerable amount of suitable habitat. The egg incubation experiments document that water quality is suitable for successful spawning. Future telemetry studies conducted on adult American shad transplanted into my study area will be valuable in field-testing these results. Future sampling for out-migrating juveniles in the lower Roanoke River basin will also be valuable in confirming that the upper basin habitat is suitable for egg development.

Studies such as this, where habitat is evaluated prior to initiation of a fish passage program, should aid in designing an effective trap-and-transport program. Results from the field surveys and habitat modeling indicate the time of year when spawning would be expected to occur and the locations that appear to have the best habitat. Adult fish could be transplanted into river reaches containing optimal habitat, or transplanted downstream of those areas and allowed to select spawning sites. Information about spawning habitat selected by transplanted fish can then be used to improve the habitat suitability models for use in other systems.

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APPENDICES

Appendix I. Temperatures (°C) measured during monthly circuit sampling. Temperature presented here is a mean value for each month from the circuit sites within each river.

Temperature						
Month	River					
	Big Otter	Stauton	Banister	Dan	Hyco	Mean
Oct-03	13.1	17.7	16.4	16.1	16.7	16.0
Nov-03	9.5	12.9	10.1	9.9	10.8	10.6
Dec-03	5.5	7.1	5.0	5.5	7.0	6.0
Jan-04	0.3	4.0	1.7	3.4	3.2	2.5
Feb-04	5.7	6.7	6.3	6.4	7.3	6.5
Mar-04	5.5	9.1	11.2	11.6	10.4	9.6
Apr-04	9.3	10.1	11.6	11.4	12.1	10.9
May-04	20.8	20.5	23.7	25.6	23.4	22.8
Jun-04	20.8	22.1	23.1	22.8	25.1	22.8
Jul-04	22.5	24.9	25.1	25.0	24.2	24.3
Aug-04	23.6	24.3	26.7	24.8	24.8	24.8

Appendix II. Turbidity (ntu) measured during monthly circuit sampling. Turbidity presented here is a mean value for each month from the circuit sites within each river.

Turbidity						
Month	River					
	Big Otter	Stauton	Banister	Dan	Hyco	Mean
Oct-03	16.2	9.9	22.7	8.2	6.4	12.7
Nov-03	13.8	12.2	20.4	10.4	5.5	12.5
Dec-03	8.6	9.6	12.5	10.5	6.7	9.6
Jan-04	10.8	12.9	9.8	6.6	8.4	9.7
Feb-04	9.3	8.7	12.3	11.3	16.9	11.7
Mar-04	7.9	8.1	21.7	7.3	8.3	10.7
Apr-04	282.0	44.4	32.1	65.5	38.2	92.4
May-04	10.8	9.0	21.3	6.8	9.0	11.4
Jun-04	31.0	21.3	73.3	98.2	15.3	47.8
Jul-04	53.3	31.3	70.5	107.6	242.0	100.9
Aug-04	25.3	34.3	20.8	20.0	12.0	22.5

Appendix III. Dissolved oxygen (mg/L) measured during monthly circuit sampling. Dissolved oxygen presented here is a mean value for each month from the circuit sites within each river.

Dissolved Oxygen						
Month	River					
	Big Otter	Stauton	Banister	Dan	Hyco	Mean
Oct-03	9.64	7.83	9.15	9.37	8.75	8.95
Nov-03	11.03	10.13	10.13	10.88	10.13	10.46
Dec-03	11.90	12.13	12.61	12.72	11.50	12.17
Jan-04	13.75	12.28	12.93	12.52	12.30	12.76
Feb-04	13.05	12.17	11.23	12.48	11.95	12.17
Mar-04	12.32	11.65	10.38	9.96	11.60	11.18
Apr-04	11.18	10.65	9.87	10.24	9.71	10.33
May-04	7.47	7.95	6.63	6.87	6.69	7.12
Jun-04	8.28	7.28	6.02	7.33	6.16	7.01
Jul-04	7.18	7.28	5.40	6.24	4.60	6.14
Aug-04	7.0	6.3	6.3	6.9	6.6	6.6

Appendix IV. Current velocity (m/s) measured during monthly circuit sampling. Current velocity presented here is a mean value for each month from the circuit sites within each river.

Current Velocity						
Month	River					
	Big Otter	Stauton	Banister	Dan	Hyco	Mean
Oct-03	0.50	0.53	0.44	0.59	0.30	0.47
Nov-03	0.64	0.49	0.53	0.56	0.26	0.49
Dec-03	0.69	0.46	0.42	0.67	0.38	0.52
Jan-04	0.92	0.40	0.49	0.64	0.51	0.59
Feb-04	0.41	0.51	0.57	0.59	0.54	0.52
Mar-04	0.45	0.31	0.36	0.43	0.25	0.36
Apr-04	0.57	0.45	0.54	0.51	0.42	0.50
May-04	0.44	0.35	0.53	0.59	0.29	0.44
Jun-04	0.27	0.28	0.35	0.37	0.19	0.29
Jul-04	0.27	0.18	0.34	0.31	0.27	0.27
Aug-04	0.26	0.21	0.29	0.34	0.13	0.25

Appendix V. pH measured during monthly circuit sampling. pH presented here is a mean value for each month from the circuit sites within each river.

pH						
Month	River					
	Big Otter	Stauton	Banister	Dan	Hyco	Mean
Oct-03	7.2	7.3	6.9	7.1	7.0	7.1
Nov-03	6.8	7.3	6.4	6.6	6.4	6.7
Dec-03	6.5	7.1	7.0	7.1	6.9	6.9
Jan-04	7.3	7.4	6.9	6.9	7.2	7.1
Feb-04	7.0	7.6	7.3	7.3	7.3	7.3
Mar-04	7.1	7.8	7.6	7.4	7.6	7.5
Apr-04	6.8	7.2	7.1	7.0	7.0	7.0
May-04	7.5	7.7	7.4	7.4	7.2	7.4
Jun-04	7.0	7.0	6.5	6.7	7.1	6.9
Jul-04	6.6	7.0	6.9	6.6	6.4	6.7
Aug-04	7.5	7.5	7.0	7.1	7.4	7.3

Appendix VI. Conductivity (µS) measured during monthly circuit sampling. Conductivity presented here is a mean value for each month from the circuit sites within each river.

Conductivity						
Month	River					
	Big Otter	Stauton	Banister	Dan	Hyco	Mean
Oct-03	87.7	132.3	76.1	149.0	109.1	110.8
Nov-03	75.2	143.6	73.8	120.4	119.1	106.4
Dec-03	71.2	126.9	69.7	111.1	104.8	96.7
Jan-04	39.2	131.9	34.5	137.6	114.3	91.5
Feb-04	73.7	134.3	69.3	123.2	108.3	101.8
Mar-04	74.6	141.8	71.2	131.4	98.1	103.4
Apr-04	77.1	127.7	71.1	106.7	103.3	97.2
May-04	69.7	149.4	76.2	178.1	122.1	119.1
Jun-04	91.1	158.7	64.9	97.6	152.3	112.9
Jul-04	92.9	145.8	66.6	104.0	79.8	97.8
Aug-04	102.0	158.7	76.1	178.2	145.0	132.0