ABSTRACT

FISK, JAMES MICHAEL, II. Reproductive Ecology and Habitat Use of the Robust Redhorse in the Pee Dee River, North Carolina and South Carolina. (Under the direction of Dr. Thomas J. Kwak).

The robust redhorse *Moxostoma robustum* is a potamodromous, imperiled riverine species rediscovered in the Pee Dee River of North Carolina and South Carolina. Due to anthropogenic processes, including habitat fragmentation and alteration from dams, the robust redhorse persists as a small remnant population in the Pee Dee River. Blewett Falls hydro-facility, the terminating hydroelectric dam on the Pee Dee River, is implementing a new minimum flow regime to create more stable habitats during critical periods for aquatic organisms including diadromous and resident fishes. The objectives of this study were to describe robust redhorse habitat suitability, quantify suitable habitat before and after the implementation of a new minimum flow regime, describe how robust redhorse use this habitat, and assess egg and larval survival associated with flow augmentation.

I implanted adult robust redhorse with radio-transmitters and relocated fish from February 2008 to July 2009. Robust redhorse were found in moderate to deep waters associated with bedrock or sandy substrates with coarse woody debris or boulders for cover. Deviations in microhabitat use occurred when robust redhorse moved into shoal habitats during the spawning period. Spawning habitat consisted of shallow waters with moderate to high velocities and gravel substrates. Except for spawning and post-spawning migrations, robust redhorse were generally sedentary making only localized movements. After spawning, a group of telemetered fish migrated downstream from the Piedmont region into the Coastal Plain, while other fish stayed in close proximity to spawning grounds, revealing two behavioral subgroups. Habitat suitability indices were developed based on field

microhabitat measurements and applied to model weighted usable area (suitable habitat quantity) for proposed minimum flows. Weighted usable area increased for each proposed seasonal minimum flow for both spawning and non-spawning periods, relative to current minimum flows.

A laboratory experiment was conducted to understand the effects of spawning redd dewatering on robust redhorse eggs and larvae. Eggs and larvae were subjected to different dewatering treatments, mimicking different hydropeaking regimes. Eggs withstood some degree of dewatering, but once larvae hatched and were free-swimming and dependent on gills for respiration, dewatering was fatal.

My results will contribute to understanding the ecology of a rare, imperiled fish and help conserve and manage this elusive species in regulated rivers. Hydroelectric facilities can use these findings to manage discharge more effectively and create and maintain important aquatic habitats during critical time periods for priority species.

Reproductive Ecology and Habitat Use of the Robust Redhorse in the Pee Dee River, North Carolina and South Carolina

by
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Biography

I was born in Wilmington, North Carolina, to Donna and James Fisk on the 25th of November, 1979. Some of my earliest memories are of pulling croakers and spots out of Buzzard's Bay, down at the mouth of the Cape Fear River. As a child, my father and pawpaw taught me how to fish and hunt and I enjoyed learning about and experiencing the natural world. My mother embraced these outdoor activities which have become lifelong pastimes.

I graduated from Laney High School in 1998 and went to Elon College to play football but was not really sure what I wanted to study. After a year of football and realizing this was not what I wanted to do, I took time off from school and worked as a carpenter for nine months. Following the advice of a friend and finding a major that sounded interesting, I enrolled in North Carolina State University's Fish and Wildlife Program. After graduating in the spring of 2004, I took a job with graduate student Ed Malindzak studying flathead catfish on the Deep River in North Carolina. Enjoying the work, I worked with the North Carolina Cooperative Fish and Wildlife Research Unit on multiple projects for several years before having the opportunity to pursue a Master's degree with Dr. Tom Kwak. After completing this degree, I hope to find a job that focuses on the conservation and restoration of the unique habitats and animals around us.

Acknowledgments

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There are many folks to thank at North Carolina State University. I appreciate Wendy Moore's help over the years as a student and employee. To my predecessors Ed Malindzak and Jessica Bauman, I thank them for their advice on graduate school, and their friendship. I am indebted to my field technicians for all their hard work and patience, Tracy McCulloch, Angel Hammers, Mills Reagon, and Andrew Rominger. Scott Favrot assisted in preliminary sampling and Ben Wallace and Dan Weaver helped collect valuable field data. Elissa Buttermore and Justin Dycus provided logistical support. I thank my officemate Patrick Cooney, for his willingness to assist me both in the office and out on the river on short notice and Christin Brown for her help in keeping this project running during chaotic times. I thank all of my fellow graduate students for their friendship, assistance, and support.

I offer my most sincere thanks to my family for their encouragement and understanding. I thank my dad for always being ready to wet a hook on the Northeast and my mom for her endless amount of encouragement. Above all, I thank my wife, Martha, for enduring this long venture with patience, love, and support.

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Chapter I — Robust Redhorse Habitat Use and Suitability in the Pee Dee River, North Carolina and South Carolina

Abstract

The robust redhorse *Moxostoma robustum* is a potamodromous, imperiled riverine species rediscovered in the Pee Dee River of North Carolina and South Carolina. Due to anthropogenic processes, including habitat fragmentation and alteration from dams, the robust redhorse persists as a small remnant population in the Pee Dee River. Blewett Falls hydro-facility, the terminating hydroelectric dam on the Pee Dee River is implementing a new minimum flow regime to create more stable habitats during critical periods for aquatic organisms including diadromous and resident fishes. My objectives were to describe robust redhorse habitat suitability, quantify suitable habitat before and after the implementation of a new minimum flow regime, and describe how robust redhorse use this habitat. I implanted radio-transmitters into adult robust redhorse and relocated fish from February 2008 to July 2009. Robust redhorse non-spawning habitat consisted of moderately deep pools (2.5 m) associated with sandy substrates with coarse woody debris or boulders for cover, and spawning habitat consisted of shallow waters (< 1.5 m) with moderate to high velocities and gravel substrates associated with shoals. Microhabitat use and availability comparisons revealed robust redhorse utilize microhabitats non-randomly. Robust redhorse were most active during the spring spawning period and generally sedentary the rest of the year, making localized movements. Telemetry relocations revealed two behavioral subgroups; a resident subgroup that remained near spawning areas in the Piedmont region throughout the year, and a migratory subgroup that made extensive downstream migrations into the Coastal Plain. Habitat suitability indices were developed based on field microhabitat measurements and applied to model weighted usable area (suitable available habitat) for proposed minimum flows. Weighted usable area increased for each proposed seasonal minimum flow for both

spawning and non-spawning periods, relative to current minimum flows, although increases in the spawning period were more substantial. Availability of spawning period habitat for the robust redhorse is critical in management decisions for the Pee Dee River.

My results will contribute to understanding the ecology of a rare, imperiled fish and help conserve and manage this elusive species in regulated rivers. Hydroelectric facilities can use these findings to manage discharge more effectively and create and maintain important aquatic habitats during critical time periods for priority species.

Introduction

Anthropogenic processes have drastically altered aquatic systems around the world to meet water, energy, and transportation needs (Nilsson et al. 2005). As a result, these changes have created modified and regulated aquatic environments that can negatively affect different life stages of fishes and may result in imperilment or extinction (Baxter 1977). The southeastern United States has the highest freshwater fish diversity in the country and a high percentage of imperiled fishes (Williams and Miller 1990; Warren et al. 1997, 2000; Jelks et al. 2008). Nongame fish species with little commercial or recreational value have historically received relatively inadequate attention by the scientific community and therefore remain poorly understood (Cooke et al. 2004). Among these fishes are catostomids, or suckers, that are widespread in North America and common throughout the southeastern United States. The redhorse genus *Moxostoma* is the most diverse of the family Catostomidae with 17 species (Jenkins and Burkhead 1993; Cooke et al. 2004).

Redhorses are entirely freshwater species that are found predominately in North America (Breder and Rosen 1966; Jenkins and Burkhead 1993). Their reproductive ecology is generally similar among species, where fish migrate upstream in river systems to spawn during the spring over coarse substrate. Spawning takes place in shallow, fast-running water for riverine species and lake-dwelling redhorses utilize shoreline habitats. Males arrive to spawning areas prior to females and typically utilize shallow waters while females stage in deeper water nearby. Females move into shallow water where males are staging and typically a male will flank each side (Curry and Spacie 1984; Page and Johnston 1990; Kwak and Skelly 1992; Grabowski and Isely 2007a). Spawning takes place when males press against the female and all three rise anteriorly, quiver, and displace substrate with caudal and anal fins while releasing gametes; this is also known as a "trembling trio." This process is repeated, sometimes with only one or multiple males. The eggs are fertilized and deposited into the gravel substrate (Page and Johnston 1990), and eggs have been found drifting downstream of spawning aggregations (Kwak and Skelly 1992). Eggs develop with no parental care. Although redhorses tend to use the same general habitats for spawning, such as riffles and shoals, spatial and temporal differences have been found that segregate species and reduce redd superimposition and degradation (Curry and Spacie 1984; Kwak and Skelly 1992; Grabowski and Isely 2007a).

One redhorse species in the southeastern United States that has received recent attention due to its rediscovery, rarity, and imperilment is the robust redhorse *Moxostoma robustum*. The robust redhorse was first described in 1870 by Edward Cope from a fish caught in the Yadkin River near Winston Salem, North Carolina. Due to a combination of a historic lack of scientific interest for nongame species, general misidentification of *Moxostoma*, declining populations, as well as the cryptic nature of the species, the robust redhorse was essentially lost to science for 120 years before being rediscovered in 1991 from fish collected in the Oconee River, Georgia (Bryant et al. 1996). After its rediscovery, preserved *Moxostoma* specimens were re-examined from collections in the Savannah and Pee Dee rivers, and one robust redhorse was correctly identified from the Savannah River collected in 1980 and another from the Pee Dee River collected in 1985 was found. It is a deep-bodied redhorse with large pharyngeal teeth for crushing mollusks and other macroinvertebrates. Currently, the only known populations are found in the Pee Dee (North Carolina, South Carolina), Savannah (South Carolina, Georgia), and Altamaha (Georgia) drainages.

The robust redhorse is the largest of the redhorses, reaching a size of 793 mm and 8,450 g. They are almost entirely mainstem river inhabitants that use shallow, gravel-bottom riffles and shoals to spawn from April to June. Temperature and river discharge play a significant role as spawning cues, and spawning takes place when water temperatures range from 17 ºC to 24 ºC (Ruetz and Jennings 2000; Freeman and Freeman 2001; Grabowski and Isely 2007a; R. Heise, North Carolina Wildlife Resources Commission, personal communication). They also exhibit typical redhorse spawning behavior where they spawn in high-velocity shallow water, over gravel substrate in a trembling trio (Page and Johnston 1990; Jenkins and Burkhead 1993; Freeman and Freeman 2001; Grabowski and Isely 2007a).

Like other redhorse species, robust redhorse are potamodromous, in that they inhabit freshwater riverine systems and make seasonal upstream migratory runs within the same river system (Breder and Rosen 1966; Grabowski and Isely 2006). The benefits of potamodromy and migration in general may exist in spatiotemporal changes in productivity. Many tropical catfish migrate hundreds of kilometers upstream to take advantage of floodplains during seasonal rainy periods to spawn and leave larvae to utilize these newly inundated habitats that are rich in resources (Northcote 1978). Migration can compensate for seasonal spatial variations in food as well as seeking refuge from unfavorable conditions. Spawning migrations compensate for the separation of growth and reproductive habitats, as these are rarely the same (Northcote 1984). This strategy also ensures that only fish that are physically able to migrate, spawn, and pass along their genes (Northcote 1984). Migration can also offset downstream drift and ensures distribution of drifting larvae into appropriate habitats. Lithophilous species like the robust redhorse utilize high flows to spawn over gravel substrate. These high flows flush out sediment in the interstitial space of the gravel and provide refuge for the eggs and larvae to develop. Although there are some disadvantages to migrating such as increased energy expenditure, predatory encounters, and larval drift into unsuitable habitats, the physical and ecological benefits outweigh the costs (Northcote 1978).

The robust redhorse, like other fish species, has been negatively affected by introduced species, degraded water quality, habitat modification, and fragmentation as a result of hydroelectric dams (Riciardi and Rasmussen 1994; Warren et al. 1997, 2000; Cooke et al. 2005). Where introduced, flathead catfish *Pylodictis olivaris* have been found to negatively impact native fish species (Thomas 1993; Ashley and Rachels 1998; Weller and Robbins 1999; Pine et al. 2007) and introduced blue catfish *Ictalurus furcatus*, although less studied, may potentially exert similar effects as larger blue catfish's diets are mainly piscivorous (Graham 1999; Edds et al 2002). Endocrine active compounds (EACs) can affect developing fish and result in intersex, the presence of both male and female gonads in an individual. EACs are likely to affect fishes in the Pee Dee River, where a high percentage of intersex largemouth bass *Micropterus salmoides* have been found (Hinck et al. 2009). EACs, including therapeutic, pharmaceutical by-products, pass through waste water treatments plants largely intact, and the effects of EACs on robust redhorse are unknown. The effects of sedimentation on spawning redds is also a concern in the Pee Dee River. Jennings et al. (2010) have shown in a laboratory experiment that robust redhorse egg mortality increases with sedimentation.

Dams block fish and invertebrate migratory routes, alter tailwater conditions by flow regulation, and create reservoirs (Collier et al. 1996; Bigford 2004; Young and Isely 2007; Waples et al. 2007) resulting in declines of redhorse species (Jenkins and Burkhead 1993;

Travnichek and Maceina 1994; Warren et al. 2000; Quinn and Kwak 2003). Altered flows from dams have also been implicated in reducing seasonal variations that can potentially affect seasonal cues by fish (Cushman 1985), loss of spawning habitats (Tyus and Karp 1990), and degraded larval nursery habitats (Robinson et al. 1998). Water level fluctuations from hydropeaking operations can result in dewatering of redds and nest superimposition, which could potentially lead to nest degradation or failure (Grabowski and Isely 2007b). Pulsed high velocity water flows that mimic hydropeaking have been found to negatively affect larval robust redhorse and v-lip redhorse *Moxostoma pappillosum*, growth as well (Weyers et al. 2003).

Rivers are dynamic and fluctuate under natural conditions. Annear et al. (2004) and references cited therein discussed how these fluctuations have different affects on individual species and yield costs and benefits in overall river productivity. Droughts can negatively affect fish species through degradation of abiotic conditions, such as dissolved oxygen and temperature, but may also result in positive effects by increasing habitat complexity, producing organic inputs, and reducing sediment deposition. Sustained drought conditions and low flows, however, can lead to habitat alteration and negative biological consequences.

At the other extreme, flooding has been found to displace fish eggs and fry, cover eggs with sediment, and reduce food availability (Annear et al. 2004). There is also evidence that when a river moves onto its floodplain, it can benefit fish reproduction by increasing spawning habitat, food availability, juvenile habitat, and juvenile refuge from main channels. While natural river fluctuations are inherently variable, unnatural river fluctuations in intensity and duration from dams can negatively affect invertebrate and fish population density and fish, aquatic plant, and benthic invertebrate productivity. Designating minimum discharges has been shown to benefit riverine fish species like the robust redhorse (Travnichek et al. 1995; Lamouroux et al. 2006).

Many of the hydroelectric dams that impair fish and other aquatic species were built in the early 1900s, before such ecological consequences were fully understood (Collier et al. 1996). Currently, hydroelectric facilities are regulated through the Federal Energy Regulatory Commission (FERC), an independent agency within the United States Department of Energy whose primary responsibilities are to regulate the interstate transmission of electricity, natural gas, and oil (FERC 2008). FERC reviews proposals for natural gas terminals, pipe lines, and relicensing for hydropower projects; it currently oversees 1,700 hydroelectric projects, and its Hydropower Commission is responsible for relicensing existing projects. An environmental assessment or an environmental impact statement is prepared by the hydroelectric project's staff or consultants, and the Commission bases recommended license conditions on these reviews in consultation with appropriate natural resource agencies. The Federal Power Act gives the Commission its legal authority, but dam operators must also comply with other federal statutes concerning environmental aspects, such as the Clean Water Act and Endangered Species Act (FERC 2008).

One such hydroelectric dam regulated by FERC is the Blewett Falls hydro-facility in south-central North Carolina near the town of Rockingham. The Blewett Falls hydro-facility is a six-unit, 22-MW facility. Its dam creates Blewett Falls Lake with 55 linear km of shoreline at full pool level at an elevation of 53 m above sea level (Progress Energy 2006). Blewett Falls Dam was completed in 1912, is 25 km north of the South Carolina state line, and is used for flood control and hydropower production (Progress Energy 2006). Blewett Falls Lake is approximately 1,036 ha and is the terminal impoundment of eight mainstem dams on the Yadkin-Pee Dee River. Average annual discharge from the dam is 224 m^3/s (7,910 ft^3/s); (USGS 2008). The 1958 license prescribed minimum flow is 4.2 m^3/s (150 ft^3/s), but Blewett Falls hydro-facility tries to maintain flows above 7.1 m^3/s (250 ft^3/s). When power generation ceases the spillage over the dam is approximately 11.3 m^3/s (400 ft^3/s). Dam spillage can drop below this level but rarely does.

An instream flow study was completed as part of the environmental assessment associated with the FERC relicensing process for Blewett Falls hydro-facility (Progress Energy 2006). The minimum flows proposed in a relicensing agreement for Blewett Falls hydro-facility to take effect in 2009, were February 1 to May 15, 68.0 m^3/s (2,400 ft^3/s), May 16 to May 31, 51.0 m^3/s (1,800 ft^3/s), June 1 to January 31, 34.0 m^3/s (1,200 ft^3/s) (Progress Energy 2006). Currently, the 401 certification is under litigation, and the hydro-facility is operating under an annual license similar to the 1958 license agreement. Some experimental flows have been implemented to mimic the proposed flows, as well as down ramping exercises to help alleviate downstream drastic fluctuations in water surface levels. The proposed minimum flows were developed to increase spawning habitat for diadromous species such as American shad *Alosa sapidissima* and striped bass *Morone saxatilis*, as well as the robust redhorse.

The river reach downstream of Blewett Falls Dam is the only known spawning area in the Pee Dee River for robust redhorse, and little is known about the reproductive ecology of this fish in the Pee Dee River or other southeastern United States rivers. The river downstream of Blewett Falls Dam is regulated by dam releases following a hydropeaking hydrograph (USGS 2009). Short term energy demands dictate when Blewett Falls hydro-facility generates power, which frequently results in hydropeaking. As dam water discharge rapidly increases and inundates areas previously with little or no water, redhorse or other fish species may utilize such areas for spawning or other ecological functions, but those areas become dewatered when hydroelectric production ceases and flows are reduced. This phenomenon is considered a type of ecological trap (Battin 2004) that has been documented for Kokanee salmon *Oncorhynchus nerka* (Stober and Tyler 1982), Chinook salmon, *Oncorhynchus tshawytscha* (Hawke 1978; Bauersfeld 1978; McMichael et al. 2005), brown trout *Salmo trutta* and steelhead (Becker et al. 1985), rainbow trout *Oncorhynchus mykiss* (Becker et al. 1985; Pender and Kwak 2002), and recently documented on the Savannah River for the robust redhorse (Grabowski and Isely 2007b). Anecdotal evidence of redd dewatering on the Pee Dee River also exists for the robust redhorse. Although the habitat is temporarily suitable while water levels are elevated, it is degraded as water levels recede and redds are dewatered. The specific effects of redd dewatering have only been studied in salmon, and the effects on robust redhorse egg and larval success are unknown. Weyers et al. (2003) found robust redhorse larvae stayed in gravel substrate for 5-10 days after hatching before emerging under experimental conditions, which could prolong the need for adequate water level and flow for larval fish survival.

After the robust redhorse was rediscovered, a memorandum of understanding was established and the Robust Redhorse Conservation Committee was formed from public, private, conservation, state and federal agency, and academic stakeholders. This committee is responsible for directing the recovery of this species and includes several technical working groups. Sampling efforts from 1999 to 2009 by a multi-organizational group (Robust Redhorse Yadkin-Pee Dee Technical Working Group), have yielded 96 total robust redhorse captures of only 61 individuals from the Pee Dee River (R. Heise, North Carolina

Wildlife Resources Commission, personal communication). This low catch rate combined with a high rate of recaptured fish suggests an extremely low adult population. In other river systems, evaluations have recently demonstrated positive effects in robust redhorse populations from multi-year supplemental stocking efforts in the Savannah and Altamaha drainages (F. Sessions, South Carolina Department of Natural Resources, personal communication). Of the 61 individual robust redhorse captured in the Pee Dee River, all but two were adults. While spawning adults were targeted during annual robust redhorse surveys (i.e., boat electrofishing over spawning shoals), this trend of low catch rates, especially for juveniles is prevalent in all three drainages sampled, suggesting low spawning stock size, limited recruitment, unknown habitat utilization by juveniles, or ineffective sampling techniques. Understanding habitat requirements for adults and juveniles is vital for robust redhorse long-term survival. Thus, I propose research to help develop and enhance conservation and management practices on regulated and modified aquatic systems for robust redhorse and other riverine species. It will also provide important information about the ecology of a rare and imperiled species and evaluate the effects of flow management.

Objectives

My objectives for this study are to (1) determine robust redhorse spawning and non-spawning habitat suitability, (2) quantify suitable spawning and non-spawning habitat before and after minimum flows are implemented, and (3) describe how robust redhorse use available spawning and non-spawning habitat.

Study Area

This research was conducted on the Pee Dee River in North Carolina and South Carolina (Figure 1). The Pee Dee River originates in Wilkes County, North Carolina, in the Blue Ridge physiographic province as the Yadkin River and flows through growing urban areas between Charlotte and Raleigh, North Carolina (NCDWQ 2003). The confluence of the Yadkin and Uwharrie rivers form the Pee Dee River. From Blewett Falls Dam, the river flows southeast for 302 km through the North Carolina lower Piedmont and South Carolina Coastal Plain until it drains into the Atlantic Ocean through Winyah Bay, near Georgetown, South Carolina. The Yadkin-Pee Dee Basin in North Carolina is 18,702 km^2, with 9,434 km of streams, 9,302 lake hectares (NCDWQ 2003), and 17 subbasins with a drainage area upstream of Blewett Falls Dam of 17,712 km^2 (Progress Energy 2006). It is the second largest river basin in North Carolina and makes up 15.9% of all streams in the state, flowing through 22 counties and 93 municipalities (NCDWQ 2003).

Historically, robust redhorse traveled upstream into the Piedmont physiographic region of North Carolina where Cope (1870) first described the species, but since its rediscovery none have been collected upstream of Blewett Falls Dam and it is likely extirpated from this reach. Currently, the only documented spawning areas are downstream of Blewett Falls Dam. The dam is one of eight mainstem dams and is a 23-m high concrete structure that has no fish passage device allowing upstream migration. Flash boards, 1.2 m high, are attached to the top of the dam adding to the reservoir's water holding capacity.

My primary study reach of the Pee Dee River begins upstream near Rockingham, North Carolina, at river km 302 from Blewett Falls Dam tailrace and continues downstream to near Cheraw, South Carolina, at river km 265 (Figure 1). The river reach from Blewett

Falls Dam down to the vicinity of Cheraw, South Carolina (approximately 37 river-km) flows through the Piedmont physiographic region and the fall line or fall zone which is composed of isolated large complex systems of shoals, runs, and pools (Progress Energy 2006).

Methods

Radio Telemetry

Robust redhorse sampling during this two-year study was part of the monitoring goals of the Robust Redhorse Yadkin-Pee Dee River Technical Working Group. Since 2000, this group has conducted annual sampling for robust redhorse, and in recent years, sampled during a three-week period from the end of April into May when conditions are ideal for robust redhorse spawning. Each year water releases from Blewett Falls hydro-facility are scheduled to coincide with sampling efforts for two reasons. First, when the Blewett Falls hydro-facility is not generating power and subsequently not releasing water, the Pee Dee River is not navigable for most electrofishing boats for over 32 kilometers downstream. Secondly, robust redhorse use these flows to access shallow habitats for staging and spawning, rendering them vulnerable to capture by boat electrofishing.

Nineteen adult robust redhorse were captured using multiple electrofishing boats with Smith-Root 2.5–7.5 GPP electrofishing units with pulsed DC current (120 Hz) at 4.0–5.0 A and implanted with radio transmitters (Table 1). Fish were captured on 22, 23, and 24 of April, 2008, and the 2, 6, and 7 of May, 2008. One adult was captured from the Coastal Plain reach on the 6 of Oct, 2008. An additional 11 robust redhorse were captured on 29 and 30 of April, 2009, and 5, 6, and 12 of May, 2009. Captured fish were weighed in grams and measured in total length to the nearest millimeter. The sex and reproductive condition were determined for each fish by gamete expression and tuberculation. A passive integrated transponder (PIT) tag was implanted into the muscle tissue just below the dorsal fin with a unique identifying number. An Advanced Telemetry Systems Model F1850 radio transmitter (40.000–41.999 MHz frequency, mean weight of 23.5 g ± 0.60 g SD, and mean displacement of 15.1 cm^3 ± 1.3 cm^3 SD) with a trailing wire antenna was surgically implanted into the peritoneal cavity of robust redhorse. Fish were anesthetized in an aerated cooler containing 30 L of river water and 43 mg/L of benzocaine solution for 3–5 min or until the fish lost equilibrium. The fish was then placed into a plastic container filled with 20 L of river water and 21.5 mg/L of benzocaine solution. Four to six scales were removed anterior to the pelvic girdle, offset from the midline to prepare for the incision. An incision was made just large enough for the transmitter's diameter, and it was inserted completely into the peritoneal cavity with the wire antenna oriented toward the caudal fin.

Trailing external antennas may irritate the area where they exit the body and may lead to infection and mortality (Matheney and Rabeni 1995), which is especially important for bottom dwelling fish such as the robust redhorse. Therefore, we gently pushed the wire antenna of the transmitter inside the peritoneal cavity where it loosely coiled so all components of the transmitter were inside the fish. The tip of each transmitter antenna was dipped in 3-mm Scotchcast resin to prevent peritoneal irritation. Incisions were sutured using sterile synthetic, absorbable suture material (coated VICRYL) with a 36-mm 0.5cm reverse cutting needle every 4–6 mm with a surgeons knot. Once the incision was closed, fish were placed into an aerated tank of river water to regain normal equilibrium and operculur movement. Fish were released into calm water in the same general area of their capture location.

Seasonal Habitat Use

To quantify robust redhorse microhabitat characteristics, radio telemetry was used to relocate undisturbed fish. Unlike some other fish species, robust redhorse do not exhibit tagging fall back and spawning behaviors appear to override any effects of tagging (R. Heise North Carolina Wildlife Resources Commission, personal communication; C. Jennings, Georgia Cooperative Fish & Wildlife Research Unit, personal communication); thus, all location data were included in analysis. Telemetered robust redhorse were relocated using an Advanced Telemetry Systems Model R2100 receiver and a hand-held loop antenna. From the Yadkin-Pee Dee Technical Working Group's 2007 sampling efforts, there were seven telemetered robust redhorse that I located at the beginning of this study, once in February, 2008 and three times in March. Starting on April 4, fish were generally located every other day until May 15, which is the known spawning period for robust redhorse in the Pee Dee River. After this time period, fish were located weekly until July 30, 2008. Fish were then located monthly from August 2008 to February 2009. Relocations were weekly for the month of March 2009 and every other day from April-May, 2009 (spawning period). Relocations were weekly from June-July, 2009, (post-spawning period). The robust redhorse spawning period was delineated as April 15 to May 15, based on the following criteria: robust redhorse made a distinct upstream migration and utilized shallow, fast-flowing habitats, water temperatures were between 15.9 and 26.3 °C (known spawning range for the Pee Dee River robust redhorse), and fish captured were displaying physical spawning characteristics, such as tubercles, loss of mucus on females, bruised and worn anal and caudal fins, and expressing gametes with little or no manual pressure. Spawning and non-spawning period habitat relocations were differentiated when robust redhorse made a distinct downstream migration or migrated off spawning shoals into deeper waters.

Once a fish was located and exact position determined, a suite of location and habitat measurements was collected. A hand-held global positioning system unit (Garmin Model GPS 5) determined geographic coordinates. Depth was measured to the nearest cm with a boat-mounted winch with a suspended 22.6-kg lead torpedo weight in non-wadeable habitats, and a top-set wading rod was used in wadeable habitats. A Marsh-McBirney Model 2000 digital flow meter was attached to either the torpedo or wading rod to measure water velocity. Mean column velocity was measured at 60% of the water column in depths up to 0.75 m and at 20% and 80% of the water column and averaged at depths greater than 0.75 m. Bottom velocity was measured at the substrate. Substrate was sampled at each location with a petit ponar dredge and dominant and subdominant substrates were visually estimated. Substrates were classified using a modified Wentworth particle size scale (Bovee and Milhous 1978; Tables 2-3). Physical cover was tactically sampled with either the petit ponar dredge or metal rod in a one 1-m^2 area around the relocation point; cover was considered as any substrate or object that could be used as overhead cover or velocity refuge by a robust redhorse.

Spawning Habitat

Throughout this study, robust redhorse could not be observed spawning due to turbid conditions that occurred with suitable spawning flows. During periods of reduced flows, water clarity improved, but robust redhorse were not observed utilizing shallow habitats under such conditions. At each electrofishing capture location during the spawning period, a weighted buoy marker was deployed and microhabitat characteristics were measured. The precision of this location relative to the fish's undisturbed microhabitat may be variable and influenced by the electrical field from the boat electrofisher and moves before succumbing to narcosis and capture (Larimore and Garrels 1985). To account for this unknown precision, microhabitat characteristics were later collected in a 20 x 20 meter grid every square meter to describe spawning habitat under similar flow conditions as those during capture at a mesohabitat scale, rather than at a microhabitat scale. Habitat variables were depth (m), bottom and mean velocity (m/s), substrate, and cover. The grid was delineated based on a combination of GPS coordinates and site descriptions with the capture location forming the center of the grid, and a center transect oriented parallel to the river flow. If a fish was captured close to the bank, microhabitat was measured up to the water-bank interface.

Each capture location was revisited during low flow conditions, and habitats were visually assessed to determine if it was indeed a spawning area or a staging area. Telemetry relocations, site fidelity of previous years and substrate characteristics of spawning conditions in other drainages were taken into consideration when making this decision. Fifteen capture locations were determined to represent spawning habitat by this assessment. Locations that were obviously not spawning areas (i.e., sand deposits downstream of an island) were excluded as in the case, no river dwelling *Moxostoma* species have been found spawning over only sand (Breder and Rosen 1966).

Microhabitat Use and Availability

Microhabitat characteristics were measured for each relocated robust redhorse, and microhabitat availability data were collected by Progress Energy (Progress Energy 2006). They collected microhabitat data at different flows along 52 cross-sectional transects from Blewett Falls Dam downstream 144 km into the Coastal Plain of South Carolina. The flow ranges consisted of a low (31–40 m^3/s), middle (87–99 m^3/s), and high (185–209 m^3/s) calibration for 31 transects in the Piedmont reach and a low (27–34 m^3/s) and high (223 m^3/s) calibration flow range for 21 transects in the Coastal Plain reach. Along each transect an acoustic Doppler current profiler (ADCP) collected depth and mean column velocities in areas navigable by a boat, and a top-set wading rod was used in shallower areas. Substrate and cover were visually estimated or tactically felt with a metal rod. These data were used to model habitat availability for species of interest including the robust redhorse for specific life history periods throughout a range of discharges to select new minimum flows.

Habitat suitability is typically calculated by dividing habitat use by availability and standardizing to a maximum index of 1.0. Availability data are usually collected at base or "normal" flows, but for a regulated river like the Pee Dee, available habitat changes with the volume of water being released. This leads to fluctuating amounts and quality of available habitats.

I used existing data from Progress Energy's (2006) surveys to estimate total available habitats from the Piedmont and Coastal Plain reaches at variable flow rates from 10 m^3/s up to 500 m^3/s using RHABSIM software (Payne and Associates 1998). The minimum flow that spills over the dam when the Blewett hydro-facility is not generating power is approximately 11.3 m^3/s, and 500 m^3/s is the maximum recommended model extrapolation

(Payne and Associates 1998; Progress Energy 2006). Although flows can be lower than 11.3 m^3/s this is a rare occurrence and thus was not modeled. Habitat availability was modeled from 10 m^3/s to 500 m^3/s in 5 m^3/s increments.

Microhabitat data for each fish relocation were stratified spatially into two reaches (Piedmont and Coastal Plain) and temporally into a spawning period (April 15 to May 15) and a non-spawning period (rest of the year). The two river reaches Piedmont and Coastal Plain, are physically distinct, which warrants separating them as two sites (Figure 1). I delineated each reach based on being upstream (Piedmont) or downstream (Coastal Plain) of the US Highway 1 Bridge (rkm 265) at Cheraw, South Carolina. The Piedmont reach is higher gradient and consists of pools and complex shoals, while the Coastal Plain is typically lower gradient with a "U" shaped river channel and the river meanders with oxbows becoming more common farther downstream. Bedrock dominates the river substrate in the Piedmont reach while sand is most abundant in the Coastal Plain reach (Figure 2). Over 50% of the habitat in the Piedmont reach is 1 to 2 m deep, while the Coastal Plain reach's depths are more evenly distributed with a mode from 0 to 0.5 m (Figure 3). Mean velocities in the Piedmont reach extend higher than those in the Coastal Plain reach under normal conditions (Figure 4). Boulders are the most abundant cover type in the Piedmont reach, while they are all but absent in the Coastal Plain reach where coarse woody debris is most abundant (Figure 5).

There were 195 fish relocations in the Piedmont reach during the spawning period, 573 relocations for the Piedmont reach during the non-spawning period, 46 relocations for the Coastal Plain reach during the non-spawning periods, and 0 relocations for the Coastal Plain during the spawning period. Microhabitat data were compared between the 2008 and

2009 spawning periods. The 2009 period had an experimental minimum flow of 34 m^3/s, mimicking the proposed minimum flow from June 1 to January 31.

To find the approximate flow at the time of each relocation in the Piedmont reach, I used the U.S. Geological Survey gauging station 02129000 (available online at http://waterdata.usgs.gov/nc/nwis/uv/?site_no=02129000) at the US Highway 74 Bridge near Rockingham, North Carolina. Since there is a delay for water to flow downstream due to the physical attributes of the river (Dunne and Leopold 1978), a time gradient was used to compensate for this, which was based on personal observations and advice from Progress Energy hydro-facility control center and the North Carolina Wildlife Resources Commission. For example if released water took 3 hrs to reach Jones Creek Shoal from Blewett Falls Dam, and a fish was relocated at 12 pm at Jones Creek Shoal, then I would use the flow at 9 am from the gauging station located near Blewett Falls Dam. For all of the Coastal Plain reach fish, I used the U.S. Geological Survey gauging station 02130561 (available online at: http://waterdata.usgs.gov/nwis/uv?site_no=02130561) nears Bennettsville, South Carolina without a delayed time gradient.

In order to quantify available habitats at a specific flow when a fish was relocated, I partitioned all fish microhabitat use data according to flow from the U.S. Geological Survey gauging station at the time the fish was relocated into evenly spaced bins. I then calculated the proportion of a particular bin range (i.e., depth 0–0.5 m at a flow of 24 m^3/s) in a given set of availability data by dividing each bin by the sum of the availability data in that flow range. I then grouped microhabitat use data for each variable into the same bin as those of availability data and divided each microhabitat use bin value by the sum of the relocations for that reach and period (e.g., Piedmont reach non-spawning), to standardize for variable sample sizes of each reach and period. The adjusted microhabitat use value was then divided by the microhabitat availability to give a proportion of that bin range of that specific flow rate. The process was repeated for each flow range for depth, mean velocity, substrate, and cover. This analysis was not performed for bottom velocity because availability data were not available (Progress Energy 2006). Finally each bin is summed throughout every flow range to yield the proportion of microhabitat used relative to that available of each bin for that variable, and the proportions were standardized to 1.0. The Coastal Plain and Piedmont reaches non-spawning period were combined and again standardized to 1.0 to represent an overall non-spawning habitat suitability function.

Microhabitat Comparisons

All continuous microhabitat variables were analyzed with a principal components analysis (PCA). Cover was omitted because it could not be converted into a continuous variable. PCA analyzes multiple continuous variables and produces uncorrelated linear combinations, referred to as principal components that explain the greatest amount of variation. Components with eigenvalues greater than 0.99 were retained as a practical break point for each analysis (Stevens 1996; Kwak and Peterson 2007). Microhabitat use component scores were calculated from habitat availability components. A Kolmogorov-Smirnov two-sample test was used to detect significantly different distributions of microhabitat use and availability data.

Due to the variability of available habitat among flow rates, a PCA was not performed on all microhabitat use data. Instead of running individual PCAs for each 5 m^3/s flow range, 17 m^3/s, 34 m^3/s, 68 m^3/s, and 204 m^3/s were used as selected flows for available habitat. The flow 136 m^3/s was not used because of the low numbers of microhabitat use data to compare it to (N=9). These flows were selected because they represent flows throughout the range of Blewett Falls hydro-facility's normal operations and incorporate two of the three proposed minimum flows. Since the amount of relocations that fell exactly on the four flows was low, a range of microhabitat use data was used to increase the sample size and make the analysis more robust. Microhabitat use data selected to compare with the corresponding availability data were based on a range around each availability flow. Availability and use data used for each flow can be found in (Table 4).

Weighted Usable Area

RHABSIM (Payne and Associates 1998) was used to calculate the amount of available suitable habitat for robust redhorse at varying flow rates described as weighted usable area (WUA). This estimate is based on the habitat availability and the specific habitat suitability function of any species. The concept of WUA was presented by Bovee and Cochnauer (1977) and has evolved since its inception (Bovee 1978; Stalnaker et al. 1995). WUA is defined as "the sum of stream surface area within a subreach, weighted by multiplying area by habitat suitability variables (most often velocity, depth, and substrate or cover) which range from 0.0 to 1.0 each, normalized to square units (either feet or meters) per 1,000 linear units." (Progress Energy 2006). WUA does not translate into actual area of suitable habitat but indicates the relative suitability of the available habitat.

Along with habitat availability data, a habitat guild, or criteria curve must be developed based on life history characteristics of the selected species (Bovee 1986). It can be based on habitat use from any component of a species' life cycle (i.e., juvenile, spawning adult, or seasonal habitat use). To estimate WUA, the combination of all variables that meet the specified suitable criteria among available habitat is quantified, so a larger suitable range for each variable will become more generalized while a smaller range will become more specific. I created criteria curves from optimal ranges for each variable from habitat suitability indices for spawning period, spawning sites and the non-spawning period. The spawning period criteria for robust redhorse included a combination of actual spawning habitat and staging habitat (Table 5), and thus was not modeled.

Spatial Analyses

The extent of fish movement was estimated annually and seasonally as linear range for telemetered robust redhorse. Linear range is defined as the most upstream and downstream relocation for a specified time period. Kernel density estimates were also calculated annually for tagged fish with at least 30 relocations (N = 14 fish) using methods similar to those of Vokoun (2003). Fish location coordinates were imported into ArcMap 9.3.1. A flow line layer from the National Hydrology Dataset (available at http://nhdgeo.usgs.gov/viewer.htm) was used to delineate the river center line starting at Blewett Falls Dam and going beyond the farthest downstream fish relocation. The center line was divided into 10-m segments (beginning with zero at Blewett Falls Dam) and the nearest segment endpoint was identified for each location. The ArcMap output was imported into SAS 9.2 statistical software (SAS 2010) where seasonal linear range and kernel density estimates of home range were calculated using PROC KDE for the 99%, 95%, 90%, 50% levels. These percentages are estimates of where a fish utilizes a certain area for that specific percent of the time. The default bandwidth procedure (Sheather-Jones plug-in) was chosen as recommended by Vokoun (2003) and grid points were set at 10-unit intervals which corresponded with the 10-m resolution of the data. Each kernel density estimate level and associated 10-m reference points were used to determine the corresponding utilized river sections for each fish. This is the utilization distribution, which is the percentage of time a fish is estimated to be within a delineated distance, and these estimates may not be contiguous. The 50% kernel density estimate is termed the fish's core area (Vokoun 2003). The utilization distribution points were then counted and multiplied by 10 to obtain an annual linear range in meters.

Results

Captures and Radio Telemetry

In 2008, a total of 19 adult robust redhorse were collected and implanted with radio transmitters between April 22 and May 7 in North Carolina and on October 6 in South Carolina from the Pee Dee River (Table 1). Of the 19 tagged fish, 11 were females with a mean total length of 685.1 mm (SE 29.3) and mean weight of 4,097.1 g (SE 589.8), while nine were males with a mean total length of 626.9 mm (SE 13.9) and a mean weight of 3,568.9 g (SE 236.4). In 2009, an additional eleven adult robust redhorse were collected and implanted with radio transmitters between April 29 and May 12 in North Carolina from the Pee Dee River. Six of these were female with a mean total length of 658.7 mm (SE 6.0) and a mean weight of 3,919.2 g (SE 252.8) and five were male with a mean total length of 648.8 mm (SE 7.6) and a mean weight of 3,919.2 g (SE 252.8). Seven telemetered females survived from 2007 Yadkin-Pee Dee Technical Working Group sampling efforts with a mean total length of 631.4 mm (SE 29.3) and mean weight of 4,097.1 g (SE 589.8).

Ten fish expelled their tags or died within a two month period after implantation from 2008 and 2009 tags. One fish tagged in 2008 expelled its tag or died after over one year of carrying the tag. Another fish tagged in 2007 expelled its tag or died over two years of implantation. Both were females and both tags were expelled during the spawning period. Two tags malfunctioned throughout the duration of this study. One tag remained in mortality mode that doubled the pulse rate. This was confirmed by collecting the live fish during the spring sampling period. An attempt was made to replace the malfunctioning transmitter with a new one but during the surgery, the transmitter was found encapsulated with scar tissue and the surgery was considered too invasive. The other tag had a malfunctioning battery or duty cycle and was only relocated two times in the same area after implantation. Expelled tags were confirmed by locating and snorkeling down to locate tags or disturb live fish and observe movement after the disturbance. Eight of the 12 expelled tags were retrieved and six implanted in new fish. One death was confirmed at the location of a tag where robust redhorse vertebrae were found immediately downstream of the transmitter and confirmed by the North Carolina Museum of Natural Sciences. No robust redhorse that expelled its transmitter in 2008 was captured in 2009, although three fish originally captured before 2008 expelled their radio transmitter and were recaptured and implanted with a new transmitter.

Throughout each sampling period there were a large number of recaptured robust redhorse. In 2008, nine fish with PIT-tags were recaptured. Of these, seven were recaptures from previous years and two were from the 2008 sampling period. In 2009, twelve fish were recaptured. Eleven of these were from previous years and one was from the same sampling period. Of the fish collected with transmitters from previous years (N = 10), all incisions were completely healed. Fish with external antennas (2007) had a slight redness at the exit point of the antenna, while fish with internal antennas (2008) had no obvious visible marks and recapture would not have been confirmed without the use of a radio receiver or PIT-tag scanner. Two fish previously were implanted with transmitters and expelled them were implanted with new ones in 2008, and one fish implanted in 2006 had a malfunctioned transmitter that was replaced with a new one in 2009. Unlike the malfunctioning tag that was attempted to be replaced in 2008, this tag was not encapsulated in scar tissue and was easily removed.

Microhabitat Use and Availability

Microhabitat characteristics of relocated robust redhorse (N = 814; 195 during spawning, 619 during non-spawning) varied between spawning and non-spawning periods and Piedmont and Coastal Plain reaches. Robust redhorse utilized moderate depths (usually 2–4 m) in the non-spawning period and shallower depths during the spawning period (Figure 3). Mean column velocities were similar throughout the year, usually 0–0.4 m/s. Microhabitats with moderate velocity were occupied in the Coastal Plain reach and higher velocities occupied more frequently in the spawning period (Figure 4). Sand and bedrock substrates were occupied most frequently in the non-spawning period, while gravel was utilized most often in the spawning period (Figure 2). Boulders were the dominant associated cover in the Piedmont reach, and coarse woody debris was utilized most often in the Coastal Plain reach (Figure 5). Cover use was significantly different from that available ($P < 0.0001$) for all three calibration flows (Table 6). Fish in the Coastal Plain reach were almost always associated with coarse woody debris.

Seasonal comparisons of microhabitat use revealed differences between spring and other seasons (summer and winter), but summer and winter microhabitat use was generally similar. Microhabitat use was significantly different ($P < 0.0001$) for all continuous variables including mean column and bottom velocity, depth, substrate, and distance to bank when comparing spring and summer (Table 7). Mean velocity and depth were significantly different ($P < 0.0001$) when comparing spring with winter. No continuous microhabitat variable was significantly different when comparing summer and winter, and cover type use was similar among all seasons.

Males and females utilized similar microhabitats throughout the year and only slight differences were found (Table 8). During the spring, females utilized deeper, lower velocities and habitats farther from the bank, but mean velocity was the only significantly different variable ($P < 0.05$). Microhabitat use during summer and winter were generally similar, but females occupied deeper water in winter ($P < 0.05$).

Microhabitat use was significantly different for some variables between the 2008 (11 m^3/s minimum flow) and 2009 (34 m^3/s minimum flow) spawning periods. Robust redhorse relocated in 2009 were found in microhabitats with higher bottom and mean velocities ($P < 0.0001$) and closer towards the bank ($P < 0.023$) (Table 9). Depth, substrate and cover were similar between years.

Multivariate Analysis

Multivariate principal components analysis revealed two contrasting habitat components. Component 1 was a gradient from the river bank with fine substrates (low scores) increasing to the mid-channel and coarse substrates (high scores). Component 2 was a gradient from low velocity and deep water (pools; low scores) increasing to high velocity and shallow water (shoals; high scores), except for the 204-m^3/s analysis, where velocity was the only significantly loaded variable (Figure 6). For each of the flow ranges analyzed, components 1 and 2 explained at least 59% of the cumulative variance (Table 10). Components 1 and 2 were highly significant for the 17 m^3/s flow and component 2 was significant for the 204 m^3/s flow showing the importance of the variables depth and velocity (Table 11). Robust redhorse were typically restricted to deep pools with low velocity when river flow was minimal, but they occupied a wider range of available microhabitats as flow increased as demonstrated by an increase in component score variance of occupied microhabitats relative to those available as flow rate increased (Figure 6).

Spawning Habitat

Microhabitat characteristics were measured at each capture location and revealed that robust redhorse spawned in shallow depths with moderate velocities when water temperatures were from 17.5–22.1 °C (Table 12). Mean distance from the bank was 18.1 m (SE 3.0) (2008) and 17.4 (SE 4.3) (2009), and fish were predominately found over gravel substrates at 78% (2008) and 75% (2009) of locations (Tables 9, 13). Mean depth for the capture grids were 0.84 m (SE 0.34), mean bottom velocities were 0.26 m/s (SE 0.002), mean water column velocity was 0.61 m/s (SE 0.004), and the mode for substrate was very coarse gravel (Table 14, Figure 7). Overall, capture microhabitat was similar to capture grids with the most variation in bottom velocity.

Microhabitat Suitability

Habitat suitability was calculated based on microhabitat use and availability data from the Pee Dee River. Optimal depth range during the spawning period (April 15 – May 15), which includes spawning, staging, and resting behaviors, was 3.0–3.5 m (Figure 8), and optimal mean velocity was 0.0–0.1 m/s (Figure 8). There was an increase in suitability from 0.5–1.0 m for depth and from 0.8–0.9 m/s for mean velocity during the spawning period, which likely represents spawning habitat. Optimal spawning substrate was large gravel with an overall higher suitability for all gravel and cobble than during the non-spawning period (Figure 8). During the spawning period, suitability was high for sandy substrates. This habitat was usually associated with deep pools occupied during both spawning and non-spawning periods. For both periods, robust redhorse relocations were most often found not associated with cover; although when present, the optimal cover was woody debris even though boulders were most frequently utilized (Figure 8). Spawning site (capture grid microhabitat) suitability consisted of 1.0–1.5 m for depth, 0.5–0.8 m/s for mean velocity, with medium and large gravel for substrate and no cover. Spawning period habitat use and suitability combined locations for multiple behaviors, including resting, staging, and spawning, which is apparent in the trimodal distribution for depth and bimodal distribution in mean velocity (Figure 8). In contrast, the non-spawning period reflected only one behavior, demonstrated in the unimodal distribution for depth and velocity.

Weighted Usable Area

The criteria used to estimate weighted usable area were based on optimal ranges of parameters (suitability score at or near 1.0) from microhabitat use suitability indices. These parameters consisted of depth (m), mean velocity (m/s), substrate, and cover and were combined to create criteria for non-spawning period and spawning site. The spawning period criteria derived from radio telemetry relocations represented a combination of staging and spawning habitats, which were not appropriate for modeling the habitat quantity (weighted usable area). The non-spawning period criteria consisted of a depth range of 2.0–3.0 m, 0.11–0.30 m/s for mean velocity, sand as substrate, and woody debris and boulder as cover (Table 5). I applied the spawning site suitability measurements associated with spawning fish capture locations to create spawning habitat criteria to calculate weighted usable area. These criteria consisted of 1.0–1.5 m for depth, 0.5–0.8 m/s for mean velocity, with medium and large gravel for substrate, and no cover was assigned.

Weighted usable area increased at all proposed minimum flows for both the spawning and non-spawning habitats, relative to the current minimum flow (Figure 9). No suitable spawning habitat was projected (zero weighted usable area) at the current minimum flow (11.3 m^3/s) and was modeled to be highest at the peak efficiency flow (204 m^3/s) when compared to the proposed minimum flows. Weighted usable area increased by 200% at 34 m^3/s, 158% at 51 m^3/s, 172% at 68 m^3/s, and 137% at the peak efficiency flow (200 m^3/s) when compared to the current minimum flow for the non-spawning period.

Linear and Home Ranges

Robust redhorse linear ranges differed among seasons for spring, summer, and winter (Table 15). Overall, linear ranges were largest during the spring, followed by the summer, then winter. Median spring range was 10 km compared to that for summer range of 6.2 km. Winter median linear range was 2.3 km. Mean linear ranges for all seasons were larger than median ranges. Linear ranges varied widely among robust redhorse individuals, and two subgroups with distinct behavioral patterns were evident; a resident and migratory group (Table 15, Figure 10). The resident subgroup stayed in the Piedmont reach throughout the year and made localized movements during the spawning season. The migratory subgroup made substantial downstream migrations into the Coastal Plain reach of South Carolina during the non-spawning period and migrated back upstream into the Piedmont reach during spawning. The number of individuals in the migratory subgroup (N = 7) was smaller than that of the resident subgroup (N = 21) and overall, the migratory subgroup had substantially larger linear ranges as expected.

Mean weekly upstream movement for an annual period was 1.8 km, while mean weekly downstream movement was 2.6 km (Table 16). Mean downstream movement was greater, influenced largely by three fish that made large downstream movements (> 60 km). When these fish were not included, the mean downstream movement was 1.9 km, equivalent to that in the upstream direction. Mean upstream movement was greater than that downstream for winter (3.5 km) and spring (2.6 km). This reflects robust redhorse migrating upstream in late winter and spring to spawning areas. Individual spawning migrations varied widely, as some fish moved upstream quickly over long distances, while others moved incrementally upstream. Timing was also variable, with some fish arriving near spawning areas in late winter while other fish waited to move into these areas in late spring, during the peak of the spawn.

Kernel density estimates were considerably smaller than linear ranges (Table 17). Mean kernel density estimates at the 50% level were 5% of the mean linear ranges among all fish, 10% of the mean linear range for the resident, and 4% of the mean linear range for the migratory group (Table 17). At the 99% level, mean range was 50% of the linear range, 60% of the resident group range, and 48% at the migratory subgroup range. This demonstrates the sedentary nature of the robust redhorse except for seasonal migratory movements. An example of 50% and 90% kernel density estimates compared to linear range from a resident robust redhorse with disjunct kernel densities is at (Figure 11). Linear ranges differed substantially between resident and migratory subgroups (means of 7.9 km versus 64.3 km, Table 15); in contrast to kernel density estimates that varied relatively less between subgroups (means of 0.8 km versus 2.5 km, Table 17).

Eight (57%) fish occupied one continuous core area (50% kernel density estimate) while six (43%) fish occupied two core areas (Table 18). No fish had more than two core areas but multiple areas were common at higher kernel density levels. Multiple core areas did not translate into larger home ranges. The means of each multiple core area (2.5 km and 1.5 km) of the six fish were greater than the mean continuous core areas (0.8 km) of the eight fish. All core areas were within the limits of 90% areas. The position of the core area within the 90% level can give insights on directional movement. For example if the core area is located within the lower (downstream) portion of the 90% estimate, a departure from this area would suggest upstream movement. A middle position would suggest both up and downstream movements, and an upstream position would suggest downstream movements. Five (63%) of the eight fish with continuous core areas were in the lower portion of their 90% estimates. The remaining four (37%) fish had core areas in the middle of the 90% estimates. Overall, multiple core areas estimated were not equal in size and exhibited different combinations of upper, middle, and lower portions of the 90% estimate.

Discussion

Robust redhorse in the Pee Dee River occupied pool habitats with low velocity throughout the year except to spawn in shoal habitats during late spring. They are sedentary fish that make localized movements except during spawning or post-spawning periods as demonstrated by their linear home ranges and kernel density estimates. This study is the first to quantify robust redhorse habitat suitability and model how these optimal habitat parameters change with flow regulation. I also confirmed the primary spawning areas downstream of Blewett Falls Dam and the importance to conserve these limited habitats. My findings reveal that spawning habitat is affected more by discharge than non-spawning habitat and that timely flow manipulations can enhance habitat for the robust redhorse.

Robust Redhorse Behavior

No dichotomy was detected between male and female migration and residence on spawning shoals. However, considerable individual variation existed where both sexes arrived and remained on or near spawning areas throughout the spawning period. This finding is contrary to the prevailing notion that males arrive earlier than females to spawning areas (Hackney et al. 1967; Page and Johnson 1990), but a similar finding of concurrent migration between sexes was revealed for sicklefin redhorse spawning behavior (Favrot 2009).

Robust redhorse in the Pee Dee River exhibited similar seasonal potamodromous patterns as other redhorse species. Sicklefin redhorse (Favrot 2009), greater redhorse *Moxostoma valenciennesi* (Bunt and Cooke 1999), and river redhorse *Moxostoma carinatum* (Hackney et al. 1968) all occupied smaller linear ranges than those of robust redhorse.

Robust redhorse from the Savannah River (Grabowski and Isley 2006) exhibited larger seasonal ranges than those of the Pee Dee River, and may be related to limited suitable habitat and limited access to the Piedmont reaches of the river that are blocked by dams. The Pee Dee River has approximately 37 km of accessible Piedmont reach habitat, in contrast to the Savannah and Altamaha drainages, where access is more restricted (Cecil Jennings Georgia Cooperative Fisheries and Wildlife Research Unit, personal communication). In some cases, low-head dams may be traversed during high water events to reach Piedmont habitats (Grabowski and Isley 2006). Stocking efforts in the Savannah and Altamaha drainages have been initiated to address this issue by reintroducing hatchery-reared and transplanted robust redhorse above some dams into free flowing river sections, such as the Broad and Wateree rivers, South Carolina, where robust redhorse likely occurred historically.

Robust redhorse exhibited high site fidelity throughout the year. Several fish that migrated downstream into the Coastal Plain reach stayed in the same river bend throughout the summer and winter and migrated upstream only for a few weeks during spawning, then returned downstream to the same river bend. This has been observed in other redhorses including the Savannah River population of robust redhorse, as well as the sicklefin redhorse (Favrot 2009). I also observed high spawning site fidelity, where fish were caught and tagged in a specific location to later return to the same shoal during spawning the following year. Spawning habitat is restricted by the series of mainstem dams on the Pee Dee River. The holotype used to originally describe the robust redhorse was collected in the Yadkin River near Winston Salem, North Carolina, over 200 km upstream of Blewett Falls Dam. The confluence of the Yadkin and Uwharrie rivers form the Pee Dee River, and this drainage is described as the Yadkin-Pee Dee with multiple rivers flowing into it upstream of Blewett

Fall Dam. It is unknown if robust redhorse utilized any other tributary rivers upstream of Blewett Falls Dam.

Unlike other redhorses that migrate into tributaries to spawn like the shorthead redhorse *Moxostoma macrolepidotum* (Sule and Skelly 1985), black redhorse *Moxostoma dusquesnei* and golden redhorse *Moxostoma erythrurum* (Curry and Spacie 1984; Kwak and Skelly 1992), and sicklefin redhorse (Favrot 2009), robust redhorse use main channel and side channel gravel bars to spawn and reside in the main river channel the remainder of the year. Throughout the duration of my study, no robust redhorse were located in a tributary or flood-plain habitat during sampling or radio telemetry. Grabowski and Isley (2006) found radio-tagged robust redhorse in an inundated floodplain during a spring high flow event on the Savannah River, South Carolina. They hypothesized that these fish were taking advantage of flooded forest habitats previously inaccessible to feed and prepare to spawn. In my study, robust redhorse occupied side channels associated with islands during the spawning period during both springs studied. At the two primary spawning shoals below Blewett Falls Dam, islands add to shoal complexity, and robust redhorse utilize these side channels. A third spawning area has been utilized to a lesser extent; robust redhorse have been captured in a side channel at Big Island near Blewett Falls Dam (1.6 rkm downstream; Ryan Heise, North Carolina Wildlife Resources Commission, personal communication). However, these captures coincided with above normal winter and spring flows. Based on sampling by the Yadkin-Pee Dee Technical Working Group and my study, only two primary spawning areas have been documented, the Jones Creek Shoal and the Hitchcock Creek Shoal (Figures 1,12–13). Other areas including the Big Island side channel may be utilized sporadically, as no telemetered fish were relocated or fish captured in that area during spawning periods of this study.

When relocated during radio tracking, robust redhorse were usually solitary, but rarely found in groups of two or more. On two occasions during periods of low flow (~ 11 m^3/s) and warm temperature (~ 35 °C), I identified two aggregations of three and four robust redhorse in complex woody debris near the mouth of Solomon's Creek (rkm 285) in the Piedmont reach. This area may have been occupied as a thermal refuge or for higher dissolved oxygen concentration. The surface water temperature at this location was 27.9 °C, and at the river bottom, the temperature was 26.4 °C. Banish et al. (2009) found lost river suckers *Deltistes luxatus* and shortnose suckers *Chasmistes brevirostris* using shallow ground water influenced habitats when deeper waters were experiencing low dissolved oxygen. The area at the mouth of Solomon's Creek was 1.5–1.8 m deep, and bottom temperature there was similar to that in deeper (3.8–4.7 m) pools in other areas of the main channel on those days. Other aggregations occurred where multiple fish were relocated using the same woody debris complex (fallen tree) as cover, but in these instances the cover was much larger and consisted of multiple trees and relocated fish were not concentrated as mentioned above.

Telemetry data suggest that flow is an important role in initiating spawning migrations and facilitating a wandering behavior in some fish. High flow events (>340 m^3/s) during March and April of 2009 initiated local and migratory movements. Several fish moved upstream during large pulses of water, only to fall back as waters receded. This has also been documented in Savannah River robust redhorse (Grabowski and Isely 2006), sicklefin redhorse (Favrot 2009), razorback sucker *Xyrauchen texanus* (Tyus and Karp 1990; Modde and Irving 1998; Mueller et al. 2000), and paddlefish *Polyodon spathula* (Paukert and

Fisher 2001; Stancill et al. 2002). It is hypothesized that the function of this behavior is that fish are assessing potential spawning habitat, but this is difficult to demonstrate unequivocally. One fish migrated downstream (58 km) in April (before the peak spawning period) and then migrated back upstream to spawn and remained in the Piedmont reach throughout the remainder of the study. This behavior was atypical for robust redhorse but may symbolize a searching behavior for suitable spawning habitat or fish aggregations and has also been observed in razorback suckers that migrate both upstream and downstream to locate suitable spawning habitat (Tyus and Karp 1990).

The persistence of high flows may facilitate spawning upstream of the two primary spawning shoals as suggested by collections there during the 2005 sampling period by the Yadkin-Pee Dee Technical Working Group (Ryan Heise, North Carolina Wildlife Resources Commission, personal communication). Those high flows were a result of high precipitation events, and not routine management practice by the dam operator. High flows may result in spawning farther upstream, but the contrasting scenario is a greater concern. Skipped and aborted spawning has been documented in other potamodromous species like the paddlefish due to unseasonably low flows (Paukert and Fisher 2001; Firehammer and Scarnecchia 2006, 2007).

Based on telemetry and electrofishing efforts, robust redhorse only access these gravel bars associated with side channels, and to a lesser extent shoal habitats during elevated flows associated with hydropower generation at Blewett Falls hydro-facility. The gravel bars located within the shoals are unsuitable with no power generation, as robust redhorse were never located there during minimal flow conditions, and portions of these areas are dewatered at such a flow volume. Robust redhorse were rarely relocated in shoal complexes during low flow conditions (only in the spring) in the deepest portions of these staging habitats (>1 m) during the spawning period, but not over gravel bars. Robust redhorse utilized shoal habitats for staging, but when flow was minimal, robust redhorse usually staged in deeper pools near shoals.

Notable differences occurred in habitat use during the experimental 17-m^3/s minimum flow in 2009 (Table 9). Robust redhorse utilized higher velocities and microhabitats closer to the bank in 2009 than 2008. Robust redhorse may have moved closer toward the bank into new available habitats as a result of higher discharge, as similar depths were utilized but velocity was higher. Juvenile trout, when exposed to increased discharges, do not seek out other microhabitats but hold their position and are subjected to higher velocities (Shirvell et al. 1994; Vehanen et al. 2000). Although robust redhorse did move closer towards the bank in 2009, this may be the case. Even though 2009 experienced higher flows from greater amounts of precipitation throughout the experimental flow relative to the time period in 2008, it highlights the interaction of habitat availability and fish use. Telemetered robust redhorse also utilized upstream habitats for a longer duration in 2009 than during 2008. After the experimental minimum flow expired, several fish continued to utilize lower Hitchcock Creek Shoal while flows were above normal and never approached 11 m^3/s, (i.e., 2008 minimum flow) throughout the month of June 2009 as a result of regional rainfall. Once the Blewett Falls hydro-facility resumed normal operational flows where discharge dropped to 11 m^3/s, this group of fish promptly migrated downstream into deeper habitats. This remnant population of robust redhorse is dependent on the discharge of Blewett Falls hydro-facility and remains vulnerable to flow manipulations. Some species of redhorse have continued to thrive in highly modified systems (Bean and Bonner 2008), but the robust redhorse likely necessitates more specific environmental conditions to successfully complete its life cycle and persist.

Robust redhorse of the Pee Dee River followed seasonal movement patterns similar to those of robust redhorse in the Savannah River, Georgia, South Carolina (Grabowski and Isley 2006), and sicklefin redhorse *Moxostoma* sp. in the Valley River, North Carolina (Favrot 2009). Within several weeks after implanting robust redhorse with radio transmitters during their spring spawning season, a small portion of robust redhorse made long downstream migrations into the Coastal Plain reach of South Carolina, while the remainder stayed within 10 km (most within 3 km) of Jones Creek Shoal (rkm 283). Grabowski and Isley (2006) found in the Savannah River that after robust redhorse were implanted with transmitters during spawning, a similar pattern emerged, except that by mid-summer into fall, almost all fish had migrated downstream and only two fish remained near spawning areas. These two summer home ranges in the Pee Dee River were retained throughout the fall and first part of winter with only localized movement. In winter, the first significant upstream movement was observed in January. This occurred during a period of increasing photoperiod, high water events, and decreasing temperatures from December to January. During February and March, upstream fish movement continued to increase as the photoperiod and water temperature increased. All wintering Coastal Plain fish migrated upstream except for one female. This fish moved upstream of the primary spawning area during the 2008 spawning period but did not in 2009, and stayed in the lower Piedmont (Great Island, rkm 268). This area may be an undocumented spawning area, because the river is braided and contains some gravel bars but is unlikely from the lack of other telemetered fish occupying the area during the spawning period. Grabowski and Isley (2006) also found that a small number of fish appeared to skip a spawning migration but never for more than one year. This suggests that a small percentage of a robust redhorse population may skip a spawning year and are at least biennial spawners.

There were two distinguishable subgroups of robust redhorse in the Pee Dee River, resident and migrant subgroups. The concept of a fish species having mobile and sedentary subpopulations dates back at least to Funk (1957), with numerous studies that support this concept (Heggenes et al. 1991; Freeman 1995; Smithson and Johnston 1999; Schmetterling and Adams 2004). Although any genetic difference between groups is unknown, the distinct behavioral differences warrant distinction of groups. This dichotomy of a resident and migratory subgroup is found in some salmonids where a portion of the population does not migrate from their natal stream but resides there and completes their life cycle (Northcote 1997; Nelson et al. 2002). Physical differences in subgroups of resident and migratory bull trout *Salvelinus confluentus* have been found, where resident fish tend to be smaller than migratory fish (Al-Chokhachy et al. 2005). Between-subgroup size differences in the robust redhorse of the Pee Dee River were not detected but this may be the result of limited sample sizes (N = 30 resident and N = 7 migratory) (Table 19). These behavioral differences may be influenced by food availability. The exotic Asian clam *Corbicula fluminea* is very abundant in the Piedmont reach of the Pee Dee River (personal observation), and captured robust redhorse have been observed passing Asian clam shell fragments from their digestive tract. This abundance of food may outweigh the benefit of migrating downstream and only a small proportion of the population makes seasonal migrations. Another potential influence on this behavior is that robust redhorse originally occupied a much greater area of the Piedmont reaches of the Pee Dee River before modification of habitat, flow, and connectivity associated with dams, extirpated fish, leaving only the downstream margin of their former distribution suitable.

Microhabitat Use

Multivariate principal component analysis revealed that robust redhorse occupied microhabitat nonrandomly on a gradient from pool to shoal (component 2) for flow ranges tested (Figure 6). Habitat use is most restricted when Blewett Falls hydro-facility is releasing little water and suitable habitat availability is at its lowest. At these low flows, robust redhorse occupied the deepest pools available in the Piedmont reach with low velocity and fine substrates between the thawleg and bank. Microhabitat use was less restricted as flow increased (Figure 6).

Microhabitats that were occupied during the spawning period had higher velocities at all flows analyzed. Spawning fish were found in microhabitats with shallow depth and higher velocities than those of non-spawning fish. Component 1 described a gradient from bank to thawleg, and at low flow robust redhorse occupied deep pools near the bank. As flow increased, robust redhorse were found in available habitats throughout this component's range.

Habitat Suitability

The habitat suitability indices (HSI) developed from my research are the first for the robust redhorse throughout its range. Qualitative descriptions of robust redhorse habitat use have been published (Grabowski and Isely 2006) but not quantified or compared to available habitats. Habitat descriptions from the Savannah River were similar in that deeper water with woody debris was most common, but were different where Savannah River fish were found over gravel while sand was the optimal substrate in the Pee Dee River. Spatial habitat availability has repeatedly been demonstrated to affect habitat use (DeGraaf and Bain 1986; Heggenes and Saltveit 1990; Heggenes 1991; Rincon and Lobon-Cervia 1993), invalidating the use of indices based on habitat use alone. These HSI indices are important for the conservation and management of the robust redhorse and may be transferable and applicable among basins. All three drainages where robust redhorse are found are hydro-regulated, and flow releases will always be a concern to maintain available habitats for the robust redhorse and other species.

Suitability indices are an important biological component of instream flow modeling and the Instream Flow Incremental Methodology in particular (Bovee 1986), and inclusion of all of a species' life stages (i.e., spawning, non-spawning) are essential. For instance, if I only examined non-spawning habitat use which consists of moderate to deep pools, then current minimum flows may appear adequate, as pools are less sensitive to flow fluctuations (Aadland 1993). Riffles and shoals (spawning habitat) are more sensitive to flow fluctuations and without adequate flow during specific time periods, species such as the robust redhorse may not successfully spawn or progeny may not survive. Suitability functions may not always reflect specific life history functions (e.g., spawning). Habitat use during spawning periods are temporally dominated by staging habitat, while actual spawning sites are occupied only a fraction of that time. The spawning period suitability index that I developed supports this behavior (i.e., staging) in that optimal depth suitability is 3–3.5 m and reflects that robust redhorse occupied deeper waters much of the time during this period (Figure 8). Occupancy of staging habitat during the spawning period dominated the habitat suitability analysis, and actual spawning sites were not adequately represented; thus, I sought an alternative approach to quantify spawning site microhabitat suitability.

Bovee (1986) concluded that although visual observation is optimal for describing spawning habitat, a strong argument can be made for using other techniques. Deviation from a fish's "normal" behavior is one technique to detect spawning. Robust redhorse have been visually observed spawning in the Savannah and Altamaha drainages (Freeman and Freeman 2001; Grabowski and Isely 2007b), but this is not feasible in the Pee Dee River because robust redhorse spawn at moderate to high flows and conditions are too turbid. Capture locations from electrofishing have been scrutinized because fish may move from their undisturbed locations before succumbing to narcosis (Larimore and Garrels 1985). However, the physical state in which you collect fish can reveal insights on their behavior or activity. By capturing a female and one or more males together that are running milt and eggs at the same time strongly suggests that the capture vicinity is where these fish were spawning. For some rare species in turbid waters, this may be the only feasible way to describe these habitats. Tyus and Karp (1990) used similar techniques to locate razorback sucker spawning habitat, but did not quantify microhabitat in these areas. Turbid water also reduces fright bias, enhancing the likelihood that a boat electrofisher's capture location may represent a fish's undisturbed habitat, albeit with unknown precision.

Fluvial habitat can be conceptualized and described among a hierarchy of spatial scales, from drainage network to microhabitat, with varying accuracy among scales. For example, microhabitat characteristics in a 1-m^2 quadrat can change dramatically from moving as little as 1 m away from a specific point (Larimore and Garrels 1985). Microhabitats then scale up to form mesohabitats (Annear et al. 2004) with generally similar physical characteristics. It was not possible to identify and describe spawning sites at the microhabitat scale in turbid water; thus, I did so at the mesohabitat scale based on capture locations. There were three distinct gravel bars that robust redhorse occupied during spawning over the two years of study; one was located at the Hitchcock Creek Shoal and two were at the Jones Creek Shoal. These habitats were characterized by medium to coarse gravel and were associated with side channels. Although robust redhorse were captured in other areas, based on capture locations and telemetry data, these three sites are extremely similar physically and appear to be preferred habitat by adult spawning fish.

The Savannah River and Oconee River (Altamaha drainage) offer ideal conditions for observing robust redhorse spawning, which has been documented. Freeman and Freeman (2001) described spawning microhabitat for the Oconee River and Savannah River, while Grabowski and Isely (2007) described spawning microhabitat in the Savannah River. Comparing robust redhorse spawning microhabitats in the Oconee and Savannah rivers to the spawning sites I measured in the Pee Dee River, similarities and differences were found. Freeman and Freeman (2001) reported a spawning depth range of 0.43–0.73 m, and Grabowski and Isely (2007) reported a mean spawning depth of 0.74 m (SE 0.02 m). Both of these descriptions were shallower than the optimal spawning depth range of 1.0–1.5 m in the Pee Dee River. Mean velocities for both the Oconee and Savannah rivers were lower at 0.3–0.5 m/s (Freeman and Freeman 2001) and 0.24 m/s (SE 0.01) (Grabowski and Isely 2007) than 0.7–0.8 m/s in the Pee Dee River. Spawning substrates were similar for all three drainages where medium to coarse gravel was used. These differences could be from inter-basin habitat differences or that microhabitat use was not compared to microhabitat availability in the Oconee or Savannah rivers.

Weighted Usable Area

The amount of modeled suitable habitat (weighted usable area) fluctuated with an increase in discharge for the spawning and the non-spawning functions but increased overall at the three proposed minimum flows and at the peak efficiency flow, when compared to the current minimum flow (Figure 9). Weighted usable area was zero at the current minimum flow for spawning which was supported by no telemetered robust redhorse utilizing gravel bar habitats at low flows. Discharge had a greater effect on spawning habitat than non-spawning habitat, where spawning habitat increased by two orders of magnitude for the three proposed minimum flows and three orders of magnitude at the peak efficiency flow when compared to the current minimum flow. Non-spawning habitat increased 158–200% for the proposed minimum flows and 137% at the peak efficiency flow.

These fluctuations reflect the spatially heterogeneous habitats of the Pee Dee River. Without these unique habitats, such as in a channelized river that is physically homogenous, habitat would be affected similarly in quality and quantity, and habitat refuges would be scarce or absent (Garner 1997). This is not the case in the Pee Dee River where distinct habitats, and in particular shoal habitats, are comprised of diverse patches of habitats that may or may not exist at varying volumes of discharge (Figure 12–13). I was unable to model bottom velocity changes with flow, and it is notable that this variable likely represents robust redhorse microhabitat more precisely for this benthic fish. Spawning habitat (shoals) is affected more by flow than non-spawning habitat (pools) and may be a predominant limiting factor to the robust redhorse's survival.

Connor and Pflug (2004) found long-term effects from increases in minimum flows based on habitat modeling estimates similar to those in my research. Spawning salmon utilized habitats farther upstream, the occurrence of redd dewatering decreased, and fry escapement increased. Freeman et al. (2001) and Auer (1996) also found an increase in spawning fishes farther upstream after the implementation of a minimum flow regime. Pert and Erman (1994) found that rainbow trout habitat use changes with increasing flows and should be considered when developing habitat suitability functions to estimate weighted usable area. Weighted usable area based on habitat use alone or suitability indices created from habitat use from a single event should only be interpreted as a static description of a species' habitat requirements with limited application beyond that specific situation. My telemetry relocations and microhabitat measurements were spaced throughout the year at a wide range of flow conditions, and these proportions of microhabitat variable intervals among flows were comprised to create one single suitability index for a spawning and non-spawning period that may be generally applied to the Pee Dee River and perhaps to other systems once verified (Figures 2–5). Applying fish suitability indices from the same river to estimate weighted usable area may be more beneficial than a standard, generalized suitability index for a fish species, as microhabitat use is affected by numerous biotic and abiotic factors (Orth 1987). Transferability of habitat suitability indices can also be problematic as substrate and cover classifications can vary greatly (Newcomb et al. 1995), and optimal ranges classified too narrowly do not transfer well either (Conklin et al. 1996). An important point about estimating available suitable habitat is that weighted usable area does not translate into actual suitable available habitat and has been found to sometimes overestimate available suitable habitat when tested (Shirvel 1989). Rivers are dynamic systems, and a gravel bar that may be critical spawning habitat can be relocated or covered by other substrates in a single flooding event. My estimates of weighted usable area should be used as a tool to help contribute information on trends and durations in quantifying available habitats of concern, rather than precise estimates of habitat quality or quantity.

Kernel density estimates are more commonly calculated for terrestrial animals but their use in fishes is growing, including blue sucker *Cycleptus elongatus* (Neeley et al. 2009), white perch *Morone americana* (McGrath and Austin 2009), muskellunge *Esox masquinongy* (Brenden et al. 2006), and flathead catfish (Vokoun and Rabeni 2005; Malindzak 2006). Linear range accounts for the difference between the farthest upstream and downstream relocations, and kernel density reveals the internal structure of the linear range and reveals areas of high and low occupancy within the range (Voukon 2003). Crook (2004) suggested that home range shifts can be the result of physical disturbances (e.g., floods or droughts), behavioral interactions (e.g., density dependence), or a species' life history requirement (e.g., spawning). Based on my telemetry results and kernel density estimates, robust redhorse may be characterized as sedentary fish that make varying degrees of movement to spawn and to seek out non-spawning habitat. That degree of migration varies greatly (Table 15, Figure 10); and I categorized two subgroups as resident and migratory (Table 15). For the resident subgroup, the migration between non-spawning habitats and spawning habitat is very small, but the ecological significance of this movement is great. The difference in energy expenditure may provide resident robust redhorse an advantage during the spawning period.

Potential Effects of Minimum Flows

River weed *Podostemum* sp. is a native aquatic plant found in the Pee Dee River that attaches to rocky substrates and forms dense mats and strands of 1 m or more under certain conditions. I anecdotally observed that this macrophyte may negatively affect the suitability of robust redhorse spawning habitat. In 2008 and in previous years, robust redhorse were captured at a specific gravel bar in a side channel at Jones Creek Shoal. During spring sampling in 2009, this gravel bar was covered with river weed precluding robust redhorse access to the potential spawning substrate. Subsequently, no robust redhorse were captured or relocated in this area. Other gravel bars at Jones Creek Shoal were partially covered with river weed, which dictated where robust redhorse could spawn. Although native to the drainage, river weed could cover what are clearly limited spawning habitats. The observed increase in river weed may have been typical yearly variability, or may have been facilitated by the 34-m^3/s minimum flow from April 15 to May 15, 2009. The minimum flow seemed to provide ideal growing conditions, as there was an overall increase throughout the Piedmont reach of the Pee Dee River in 2009, and stable flows can increase macrophyte density and abundance (French and Chambers 1996). Other regulated rivers have experienced increases in macrophytes as a result in altered flow regimes and nutrient loading from reservoir releases upstream, and it has been demonstrated experimentally that nuisance macrophytes can be managed with pulsed flows (Flinders and Hart 2009). High flow events (> 340 m^3/s) in the Pee Dee River effectively dislodged and cleared these dense mats, but Blewett Falls hydro-facility does not have the capacity to duplicate such flows and must rely on natural occurrences. Aquatic plant habitat requirements and related effects on fish habitat suitability are not typically considered in instream flow assessments, but these anecdotal observations with river weed suggest a potentially critical, but overlooked effect.

Conservation and Management

The robust redhorse is listed as a high priority and endangered species in North Carolina (North Carolina Wildlife Resources Commission 2009). The Pee Dee River adult spawning population appears to be extremely low, estimated from 2006 to 2009 to be between 38 to 55 individuals (R. Heise, North Carolina Wildlife Resources Commission, personal communication). Habitat alteration, especially sedimentation and the construction and operation of dams, is a major issue in aquatic systems and results in reduced and modified species assemblages (Pringle et al. 2000; Bunn and Arthington 2002). The removal of any mainstem dam on the Yadkin-Pee Dee River is unlikely, and although the removal of Blewett Falls Dam would benefit the river the most among dams by allowing access to habitats for diadromous and resident fishes, the other benefits to humans outweigh this option. Thus, optimizing management of dam releases is critical, and the findings presented here can inform that process.

While my results provide a tool for assessment, long-term monitoring will be required to assess the impacts that a new minimum flow regime will have on robust redhorse habitat use and density. Few investigators have studied these effects empirically, and most have only modeled suitable available habitats as I did. Lamouroux et al. (2006) found a positive relationship with a new minimum flow regime and the fish assemblage. Harby et al. (2007) recommended long-term sampling or waiting multiple years before initiating sampling after the minimum flows are initiated because of yearly variation and the effects on fish assemblages can change gradually.

A sizable data set has been developed by the Yadkin-Pee Dee Technical Working Group on robust redhorse abundance (2000-2010) and may prove valuable as baseline data to support long-term monitoring under varying flow regimes. My findings will contribute to the ecological understanding of a rare, imperiled species and will assist management and conservation efforts. By providing suitable habitats during critical time periods, successful spawning and recruitment may be enhanced. The currently proposed minimum flows will inundate all gravel bars throughout the Piedmont reach and provide important habitat for egg and larval rearing, which is discussed in Chapter 2. Research and management effects may focus on other issues of the robust redhorse, such as juvenile habitat use which remains unknown. Currently, no young-of-year and very few juvenile robust redhorse have been collected in the Pee Dee River. Other important issues are predatory interactions from introduced blue catfish and flathead catfish, competitive interactions with the introduced smallmouth buffalo *Ictiobus bubalus* and indirect effects from exotic grass carp *Ctenopharyngodon idella*. Other native species are likely to benefit from an augmented minimum flow regime as well. Managing releases from Blewett Falls Dam to benefit the robust redhorse is an important aspect for the recovery of this species in the Pee Dee River. The results from my research will allow managers to make informed decisions about enhancing and sustaining important habitats for the robust redhorse.

Literature Cited

Aadland, L. P. 1993. Stream habitat types: their fish assemblages and relationship to flow. North American Journal of Fisheries Management 13:790–806.

Al-Chokhachy, R., P. Budy, and H. Schaller. 2005. Understanding the significance of redd counts: a comparison between two methods for estimating the abundance of and monitoring bull trout populations. North American Journal of Fisheries Management 25:1505–1512.

Annear, T., I. Chisolm, H. Beecher, A. Locke, and 12 other authors. 2004. Instream flows for riverine resource stewardship, revised edition. Instream Flow Council, Cheyenne, Wyoming.

Ashley, K. W., and R. T. Rachels. 1998. Changes in redbreast sunfish population characteristics in the Black and Lumber rivers, North Carolina. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 52:29–38.

Auer, N. A. 1996. Response of spawning lake sturgeons to change in hydroelectric facility operation. Transactions of the American Fisheries Society 125:66–77.

Banish, N. P., B. J. Adams, and R. S. Shively. 2009. Distribution and habitat associations of radio-tagged adult lost river suckers and shortnose suckers in upper Klamath Lake, Oregon. Transactions of the American Fisheries Society 138:153–168.

Battin, J. 2004. When good animals love bad habitats: ecological traps and the conservation of animal populations. Conservation Biology 18:1482–1491.

Bauersfeld, K. 1978. The effect of daily flow fluctuations on spawning fall chinook in the Columbia River. Washington Department of Fisheries Technical Report 38, Olympia, Washington.

Baxter, R. M. 1977. Environmental effects of dams and impoundments. Annual Review of Ecology and Systematics 8:255–283.

Bean, P. T., and T. H. Bonner. 2008. Diet and reproduction of the gray redhorse *Moxostoma congestum* in a Texas Hill Country stream and reservoir. Journal of Freshwater Ecology 23:397–404.

Becker, C. D., D. A. Neitzel, and D. W. Carlile. 1985. Survival data for dewatered rainbow trout *Salmo gairdneri* Rich eggs and alevins. Journal of Applied Ichthyology 2:102–110.

Bigford, T. 2004. American Fisheries Society draft study report and policy statement on dam removal. Fisheries 29(7):34–35.

Bovee, K. D., and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: fisheries. Instream Flow Information Paper 3. U.S. Fish and Wildlife Service FWS/OBS-77/63.

Bovee, K. D. 1978. The incremental method of assessing habitat potential for coolwater species, with management implications. American Fisheries Society Special Publication 11:340–346.

Bovee, K. D., and R. Milhous. 1978. Hydraulic simulation in instream flow studies: theory and techniques. Instream Flow Information Paper Number 5. U.S Fish and Wildlife Service, FWS/OBS–78/33.

Bovee. K. D. 1986. Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. U.S. Fish and Wildlife Service Biological Report 86(7).

Breder, C. M., Jr. and D. E. Rosen. 1966. Modes of reproduction in fishes. Natural History Press, Garden City, New York.

Brenden T. O., B. R. Murphy, and E. M. Hallerman. 2006. Effect of discharge on daytime habitat use and selection by muskellunge in the New River, Virginia. Transactions of the American Fisheries Society 135:1546–1558.

Bryant, R. T., J. W. Evans, R. E. Jenkins, and B. J. Freeman. 1996. The mystery fish. Southern Wildlife 1:26–35.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and consequences of altered hydrological regimes for aquatic biodiversity. Environmental Management 30:492–507.

Bunt, C. M., and S. J. Cooke. 2001. Post-spawn movements and habitat use by greater redhorse *Moxostoma valenciennesi*. Ecology of Freshwater Fish 10:57–60.

Collier, M., R. H. Webb, and J. C. Schmidt. 1996. Dams and rivers: primer on the downstream effects of dams. U. S. Geological Survey Circular 1126. Denver, Colorado.

Conklin, D. J., Jr, S. P. Canton, J. W. Chadwick, and W. J. Miller. 1996. Habitat suitability curves for selected fish species in the central Platte River, Nebraska. Rivers 5:250–266.

Connor, E. J., and D. E. Pflug. 2004. Changes in the density of pink, chum, and chinook salmon spawning in the upper Skagit River in response to flow management measures. North American Journal of Fisheries Management 24:835–852.

Cooke, S. J., C. M. Bunt, S. J. Hamilton, C. A. Jennings, M. P. Pearson, M. S. Cooperman, and D. F. Markle. 2004. Threats, conservation strategies, and prognosis for suckers (Catostomidae) in North America: insights from regional case studies of a diverse family of non-game fishes. Biological Conservation 121:317–331.

Cope, E. D. 1870. Partial synopsis of the fishes of the fresh waters of North Carolina. Proceedings of the American Philosophical Society 11:448–495.

Crook, D. 2004. Is the home range concept compatible with the movements of two species of lowland river fish? Journal of Animal Ecology 73:353–366.

Curry, K. D., and A. Spacie. 1984. Differential use of stream habitat by spawning catostomids. American Midland Naturalist 11:267–279.

Cushman, R. M. 1985. Review of the effects of rapidly varying flows downstream from hydroelectric facilities. North American Journal of Fisheries Management 5:330–339.

Degraaf, D. A., and L. H. Bain. 1986. Habitat use by and preferences of juvenile Atlantic salmon in 2 Newfoundland rivers. Transactions of the American Fisheries Society 115:671–681.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W.H. Freeman, New York.

Edds, D. R., W. J. Mathews, and F. P. Gelwick. 2002. Resource use by large catfishes in a reservoir: is there evidence for interactive segregation and innate differences? Journal of Fish Biology 60:739–750.

Favrot, S. D. 2009. Sicklefin redhorse reproductive and habitat ecology in the upper Hiwassee River basin of the southern Appalachian Mountains. Master’s Thesis. North Carolina State University, Raleigh, North Carolina.

FERC (Federal Energy Regulatory Commission) 2008. What FERC Does. Available: http://www.ferc.gov. (March 2008).

Firehammer, J. A., and D. L. Scarnecchia. 2006. Spring migratory movements by paddlefish in natural and regulated river segments of the Missouri and Yellowstone rivers, North Dakota and Montana. Transactions of the American Fisheries Society 135:200–217.

Firehammer, J. A., and D. L. Scarnecchia. 2007. The influence of discharge on duration, ascent distance, and fidelity of the spawning migration for paddlefish of the Yellowstone-Sakakawea stock, Montana and North Dakota, USA. Environmental Biology of Fishes 78:23–36.

Flinders, C. A., and D. D. Hart. 2009. Effects of pulsed flows on nuisance periphyton growths in rivers: a mesocosm study. River Research and Applications 25:1320–1330.

Freeman, M. C. 1995. Movements by two small fishes in a large stream. Copeia 1995:361–367.

Freeman, B. J., and M. C. Freeman. 2001. Criteria for suitable spawning habitat for the robust redhorse *Moxostoma robustum*. U.S. Fish and Wildlife Report. Athens, Georgia.

French, T. D., and P. A. Chambers. 1996. Habitat partitioning in riverine macrophyte communities. Freshwater Biology 36:509–520.

Garner, P. 1997. Seasonal variation in the habitat available for 0+ *Rutilus rutilus* (L.) in a regulated river. Aquatic Conservation: Marine and Freshwater Ecosystems 7:199–210.

Grabowski, T. B., and J. J. Isely. 2006. Seasonal and diel movements and habitat use of robust redhorse in the lower Savannah River, Georgia and South Carolina. Transactions of the American Fisheries Society 135:1145–1155.

Grabowski, T. B., and J. J. Isely. 2007a. Spatial and temporal segregation of spawning habitat by catostomids in the Savannah River, Georgia and South Carolina, U.S.A. Journal of Fish Biology 70:782–798.

Grabowski, T. B., and J. J. Isely. 2007b. Effects of flow fluctuations on the spawning habitat of a riverine fish. Southeastern Naturalist 6:471–478.

Graham, K. 1999. A review of the biology and management of blue catfish. American Fisheries Society Symposium 24:37–49.

Hackney, P. A., W. M. Tatum, and S. L. Spencer. 1967. Life history study of the river redhorse, *Moxostoma carinatum* (Cope), in the Cahaba River, Alabama, with notes on the management of the species as a sport fish. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 21:324–332.

Harby, A., J. M. Oliver, S. Merigoux, and E. Malet. 2007. A mesohabitat method used to assess minimum flow changes and impacts in the invertebrate and fish fauna in the Rhone River, France. River Research and Applications 23:525–543.

Hawke, S. P. 1978. Stranded redds of quinnant salmon in the Mathias River, South Island. New Zealand Journal of Marine and Freshwater Research 12:167–171.

Heggenes, J., and S. J. Saltveit. 1990. Seasonal and spatial microhabitat selection and segregation in young Atlantic salmon, *Salmo salar* L., and brown trout, *Salmo trutta* L., in a Norwegian river. Journal of Fish Biology 36:707–720.

Heggenes, J. 1991. Comparisons of habitat availability and habitat use by an allopatric cohort of juvenile Atlantic salmon *Salmo salar* under conditions of low competition in a Norwegian stream. Holarctic Ecology 14:51–62.

Heggenes, J., T. G. Northcote, and A. Peter. 1991. Spatial stability of cutthroat trout (*Oncorhynchus clarki*) in a small, coastal stream. Canadian Journal of Fisheries and Aquatic Sciences 48:757–762.

Hinck, J. E., V. S. Blazer, C. J. Schmitt, D. M. Papoulias, D. E. Tillitt. 2009. Widespread occurrence of intersex in black bass (*Micropterus* spp.) from U.S. rivers, 1995-2004. Aquatic Toxicology 95:60–70.

Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Díaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren, Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33(8):372–407.

Jenkins, R. E., and N. M. Burkhead. 1993. Freshwater fishes of Virginia. American Fisheries Society, Bethesda, Maryland.

Jennings, C. A., J. L. Shelton Jr., and R. C. Peterson. 2010. Fine sediment affects on survival to emergence of robust redhorse. Environmental Biology of Fishes 87:43–53.

Kwak, T. J., and J. T. Peterson. 2007. Community indices, parameters, and comparisons. Pages 677–763 *in* C. S. Guy and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Kwak, T. J., and T. M. Skelly. 1992. Spawning habitat, behavior, and morphology as isolating mechanisms of the golden redhorse, *Moxostoma erythrurum*, and the black redhorse. *M. dusquesnei*, two syntopic fishes. Environmental Biology of Fishes 34:127–137.

Lamouroux, N. J., M. Oliver, H. Capra, M. Zylberblat, A. Chandesris, and P. Roger. 2006. Fish community changes after minimum flow increase: testing quantitative predictions in the Rhone River at Pierre–Benite, France. Freshwater Biology 51:1730–1743.

Larimore, R. W., and D. D. Garrels. 1985. Assessing habitats used by warmwater stream fishes. Fisheries 10(2):10–16.

Malindzak, E. G. 2006. Behavior and habitat use of introduced flathead catfish in a North Carolina Piedmont river. Master's Thesis. North Carolina State University, Raleigh, North Carolina.

McGrath, P., and H. A. Austin. 2009. Site fidelity, home range, and tidal movements of white perch during the summer in two small tributaries of the York River, Virginia. Transactions of the American Fisheries Society 138:966–974.

McMichael, G. A., C. L. Rakowski, B. B. James, and J. A. Lukas. 2005. Estimated fall chinook salmon survival to emergence in dewatered redds in a shallow side channel of the Columbia River. North American Journal of Fisheries Management 25:876–884.

Modde, T., and D. B. Irving. 1998. Use of multiple spawning sites and seasonal movements by razorback suckers in the middle Green River, Utah. North American Journal of Fisheries Management 18:318–326.

Mueller, G., P. C. Marsh, G. Knowles, and T. Wolters. 2000. Distribution, movements, and habitat use of razorback sucker (*Xyrauchen texanus*) in a lower Colorado River reservoir, Arizona-Nevada. Western North American Naturalist 60:180–187.

Neely, B. C., M. A. Pegg, and G. E. Mestl. 2009. Seasonal use distributions and migrations of blue sucker in the Middle Missouri River. Ecology of Freshwater Fish 18:437–444.

Nelson, M. L., T. E. McMahon, and R. F. Thurow. 2002. Decline of the migratory form in bull charr, *Salvelinus confluentus*, and implications for conservation. Environmental Biology of Fishes 64:321–332.

Newcomb, T. J., S. A. Perry, W. B. Perry. 1995. Comparison of habitat suitability criteria for smallmouth bass *Micropterus dolomieu* from three West Virginia rivers. Rivers 5:170–183.

Nilsson, C., C. A. Reidy, M. Dynesius, C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. Science 308:405–408.

North Carolina Division of Water Quality (NCDWQ). 2003. Yadkin-Pee Dee River basinwide water quality plan. North Carolina Department of Environment and Natural Resources, Division of Water Quality, Raleigh, North Carolina.

North Carolina Wildlife Resources Commission. 2005. North Carolina Wildlife Action Plan. Raleigh, North Carolina.

Northcote, T. G. 1978. Migratory strategies and production in freshwater fishes. Pages 326–359 *in* S. D. Gerking, editor. Ecology of freshwater fish production. Blackwell Scientific Publications, Osney Mead, Oxford, United Kingdom.

Northcote, T. G. 1984. Mechanisms of fish migrations in rivers. Pages 317–339 *in* J. D. McCleave, G. P. Arnold, J. J. Dodson, and W. H. Neil, editors. Mechanisms of Migration in Fishes. Plenum Press, New York, New York.

Northcote, T. G. 1997. Potamodromy in salmonidae–living and moving in the fast lane. North American Journal of Fisheries Management 17:1029–1045.

Orth, D. J. 1987. Ecological considerations in the development and application of instream flow-habitat models. Regulated Rivers 1:171–181.

Page, L. M., and C. E. Johnston. 1990. Spawning in the creek chubsucker, *Erimyzon oblongus*, with a review of spawning behavior in suckers (Catostomidae). Environmental Biology of Fishes 27:265–272.

Paukert, C. P., and W. L. Fisher. 2001. Characteristics of paddlefish in a southwestern U.S. reservoir, with comparisons of lentic and lotic populations. Transactions of the American Fisheries Society 130:634–643.

Payne, T. R., and Associates 1998. Riverine habitat simulation software version 2.0. Thomas R. Payne and Associates, Arcata, California.

Pender, D. R., and T. J. Kwak. 2002. Factors influencing brown trout reproductive success in Ozark tailwater rivers. Transactions of the American Fisheries Society 131:698–717.

Pert, E. J., and D. C. Erman. 1994. Habitat use by adult rainbow trout under moderate artificial fluctuations in flow. Transactions of the American Fisheries Society 123: 913–923.

Pine, W.E., III, T. J. Kwak, and J. A. Rice. 2007. Modeling management scenarios and the effects of an introduced apex predator on a coastal riverine fish community. Transactions of the American Fisheries Society 136:105–120.

Pringle, C. M., M. C. Freeman, and B. J. Freeman. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the New World: tropical-temperate comparisons. BioScience 50:807–823.

Progress Energy. 2006. Application for license: Yadkin-Pee Dee River project, FERC No. 2206. Progress Energy, Raleigh, North Carolina.

Quinn J. W., and T. J. Kwak. 2003. Fish assemblage change in an Ozark river after impoundment: a long-term perspective. Transactions of the American Fisheries Society 132:110–119.

Ricciardi, A., and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220–1222.

Rincon, P. A., and J. Loboncervia. 1993. Microhabitat use by stream-resident brown trout: bioenergetic consequences. Transactions of the American Fisheries Society 122:575–587.

Ruetz, C. R., and C. A. Jennings. 2000. Swimming performance of larval robust redhorse *Moxostoma robustum* and low-velocity habitat modeling in the Oconee River, Georgia. Transactions of the American Fisheries Society 129:398–407.

Robinson, A. T., R. W. Clarkson, and R. E. Forrest. 1998. Dispersal of larval fishes in a regulated river tributary. Transactions of the American Fisheries Society 127:772–786.

Schmetterling, D. A., and S. B. Adams. 2004. Summer movements within the fish community of a small montane stream. North American Journal of Fisheries Management 24:1163–1172.

Shirvel, C. S. 1989. Ability of PHABSIM to predict chinook salmon spawning habitat. Regulated Rivers: Research and Management 3:277–289.

Shirvell, C. S. 1994. Effect of changes in streamflow on the microhabitat use and movements of sympatric juvenile coho salmon and Chinook salmon in a natural stream. Canadian Journal of Fisheries and Aquatic Sciences 51:1644–1652.

Smithson, E. B., and C. E. Johnston. 1999. Movement patterns of stream fishes in a Ouachita highlands stream: an examination of the restricted movement paradigm. Transactions of the American Fisheries Society 128:847–853.

Stalnaker, C., B. L. Lamb., J. Fienriksen, K. Bovee, and J. Bartholow. 1995. The instream flow incremental methodology: a primer for IFIM. National Biological Service, U.S. Department of the Interior. Biological Report number 29, Fort Collins, Colorado.

Stancill, W., G. R. Jordan, and C. P. Paukert. 2002. Seasonal migration patterns and site fidelity of adult paddlefish in Lake Case, Missouri River. North American Journal of Fisheries Management 22:815–824.

SAS Institute Inc. 2010. SAS/STAT User's Guide, release 9.2. SAS Institute, Cary, North Carolina.

Stevens, J. 1996. Applied multivariate statistics for the social sciences, 3rd edition. Lawrence Erlbaum Associates, Mahway, New Jersey.

Stober, Q. J., and R. W. Tyler. 1982. Rule curves for irrigation drawdown and kokanee salmon (*Oncorhynchus nerka*) egg to fry survival. Fisheries Research 1:195–218.

Sule, M. J., and T. M. Skelly. 1985. The life history of the shorthead redhorse, *Moxostoma macrolepidotum*, in the Kankakee River drainage, Illinois. Illinois Natural History Survey Biological Notes, Champaign, Illinois.

Thomas, M. E. 1993. Monitoring the effects of introduced flathead catfish on sport fish populations in the Altamaha River, Georgia. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 47:531–538.

Travnichek, V. H., and M. J. Maceina. 1994. Comparison of flow regulation effects on fish assemblages in shallow and deep water habitats in the Tallapoosa River, Alabama. Journal of Freshwater Ecology 9:207–216.

Travnichek, V. H., M. B. Bain, and M. J. Maceina. 1995. Recovery of a warmwater fish assemblage after the initiation of a minimum flow release downstream from a hydroelectric dam. Transactions of the American Fisheries Society 124:836–844.

Tyus, H. M., and C. A. Karp. 1990. Spawning and movements of the razorback sucker, *Xyrauchen texanus*, in the Green River basin of Colorado and Utah. Southwestern Naturalist 35:427–433.

U. S. Geological Survey. Real time stream flow: USGS 02129000 Pee Dee River near Rockingham, North Carolina. Available: http://waterdata.usgs.gov/nc/nwis/uv/?site_no=02129000 (March 2008).

Vehanen, T., P. P. Bjerke, J. Heggenes, A. Huusko, and A. Maki-Petays. 2000. Effect of fluctuating flow and temperature on cover type selection and behavior by juvenile brown trout in artificial flumes. Journal of Fish Biology 56:923–937.

Vokoun, J. C. 2003. Kernel density estimates of linear home ranges for stream fishes: advantages and data requirements. North American Journal of Fisheries Management 23:1020–1029.

Vokoun, J. C., and C. F. Rabeni. 2005. Home range and space use patterns of flathead catfish during the summer-fall period in two Missouri streams. Transactions of the American Fisheries Society 134:509–517.

Waples, R. S., R. W. Zabel, M. D. Mark, and B. L. Sanderson. 2007. Evolutionary responses by native species to major anthropogenic changes to their ecosystems: Pacific salmon in the Columbia River hydropower system. Molecular Ecology 17:84–96.

Warren, M. L., Jr., P. L. Angermeier, B. M. Burr, and W. R. Haag. 1997. Decline of a diverse fish fauna: patterns of imperilment and protection in the southeastern United States. Pages 105–164 *in* G. W. Benz, editor. Aquatic fauna in peril: the southeastern perspective. Lenz Design and Communications, Decatur, Georgia.

Warren, M. L., Jr., B. M. Burr, S. J. Walsh, H. L. Bart, R. C. Cashner, D. A. Etnier, B. J. Freeman, B. R. Kuhajda, R. L. Mayden, H. W. Robison, S. T. Ross, and W. C. Starnes. 2000. Diversity, distribution, and conservation status of the native freshwater fishes of the southern United States. Fisheries 25(10):7–31.

Weller, R. R., and C. Robbins. 1999. Food habits of flathead catfish in the Altamaha River system, Georgia. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 53:35–41.

Weyers, R. S., C. A. Jennings, and M. C. Freeman. 2003. Effects of pulsed, high-velocity water flow on larval robust redhorse and v-lip redhorse. Transactions of the American Fisheries Society 132:84–91.

Williams, J. E., and R. R. Miller. 1990. Conservation status of the North American fish fauna in freshwater. Journal of Fish Biology 37:79–85.

Young, S. P., and J. J. Isely. 2007. Diel behavior of adult striped bass using tailwater habitat as summer refuge. Transactions of the American Fisheries Society 136:1104–1112.

Table 1. Telemetered robust redhorse characteristics for this study. Fish that died or expelled their transmitter within 2-wks after transmitter implantation were omitted. Seven fish were tagged and survived from 2007 by the Yadkin-Pee Dee Technical Working Group. Transmitters that were reused on new fish in 2009 are denoted with a "B."

Transmitter Frequency	Capture Year	Capture Location from Dam (km)	Sex	Total Length (mm)	Weight (g)	Number of Relocations
40.021	2007	16.8	F	613	3,855	59
40.041	2007	17.2	F	592	3,475	27
40.061	2007	17.2	F	569	3,195	54
40.611	2007	20.9	F	618	3,775	47
40.631	2007	9.5	F	575	2,710	22
40.671	2007	9.6	F	793	7,460	39
40.690	2007	9.7	F	660	4,210	53
40.141	2008	17.5	F	662	4,835	26
40.540	2008	17.1	F	733	6,400	39
40.730	2008	16.2	M	601	2,630	35
40.761	2008	16.6	F	709	5,725	38
40.800	2008	17.1	M	626	3,885	39
40.810	2008	46.5	F	675	4,430	15
40.820	2008	16.4	M	576	2,760	15
40.830	2008	16.2	M	622	3,315	14
40.841	2008	16.8	M	659	4,095	32
40.952	2008	17.0	F	696	4,305	9
41.660	2008	16.7	M	588	3,145	35
41.682	2008	16.6	F	627	4,515	33
41.701	2008	9.8	M	614	3,700	21
41.720	2008	16.2	M	641	3,665	32
41.741	2008	17.0	F	648	4,390	35
40.121B	2009	9.5	F	667	5,650	14
40.531B	2009	16.9	M	659	4,295	10
40.631B	2009	16.6	F	646	4,500	14
40.790B	2009	8.7	M	624	4,010	11
41.771	2009	16.2	M	648	3,880	8
41.781	2009	8.8	M	669	2,986	10
41.789	2009	16.9	F	650	5,100	7
41.910	2009	16.9	F	653	4,345	12
Mean		16.2		644	4,175	26.8
SD		6.6		48	1,085	15.2

Table 2. Particle size categories based on modified Wentworth scale (Bovee and Milhous 1978) to describe substrate composition. Particle categories were modified (Pee Dee River) according to Progress Energy Pee Dee River Instream Flow Study (2006).

Particle category	Abbreviation	Pee Dee River	Size class (mm)	Continuous variable
Silt-Clay	ST/CL	Silt/Clay	<.062	1
Sand	SD	Sand	.062-1	2
Very Coarse Sand	VCS	Sand	1-2	2
Pea Gravel	PG	Small gravel	2-4	3
Fine Gravel	FG	Small gravel	4-8	3
Medium Gravel	MG	Medium gravel	8-16	4
Coarse Gravel	CG	Medium gravel	16-32	4
Very Coarse Gravel	VCG	Large gravel	32-64	5
Small Cobble	SC	Small Cobble	64-130	6
Large Cobble	LC	Large Cobble	130-250	7
Small Boulder	SB	Small Boulder	250-500	8
Medium Boulder	MB	Small Boulder	500-1,000	8
Large Boulder	LB	Large Boulder	1,000-2,000	9
Very Large Boulder	VLB	Large Boulder	2,000-4,000	9
Mammoth Boulder	MAB	Large Boulder	>4,000	9
Bedrock	BR	Bedrock		10

Table 3. Cover types based on modified Wentworth scale (Bovee and Milhous 1978) and modified according to Progress Energy Pee Dee River Instream Flow Study (Progress Energy 2006) for microhabitat analysis.

Particle category	Pee Dee River classification
Small boulder	BD
Medium boulder	BD
Large boulder	BD
Very large boulder	BD
Mammoth boulder	BD
Bedrock	BD
Undercut bank	UB
Submerged vegetation	SV
Emergent vegetation	EV
Fine woody debris	FWD
Coarse woody debris	CWD
Root wad	RW
No cover	NC

Table 4. Microhabitat use and availability sample sizes (*N*) used for individual components of the flow-specific principal components analysis.

Flow (m^3/s)	Total microhabitat use (*N*)	Spawning period (*N*)	Non-spawning period (*N*)	Available habitat (*N*)
17	324	68	256	9,032
34	45	34	11	9,032
68	39	30	9	9,039
204	168	28	140	10,670

Table 5. Microhabitat criteria used to model weighted usable area for proposed minimum flows. Non-spawning and spawning periods (from radio telemetry), and spawning grids (capture location grid microhabitats) are based on microhabitat suitability indices. Substrate and cover are classified using the Progress Energy Instream Flow Study (Progress Energy 2006). For substrate and cover abbreviations see Tables 2 and 3.

	Depth (m)	Mean velocity (m/s)	Substrate	Cover
Non-spawning period	2.50 - 3.00	0.11 - 0.30	sand	woody debris and boulder
Spawning period	3.10 - 3.50	0.01 - 0.20	large gravel	woody debris and boulder
Spawning site	1.00 - 1.50	0.50 - 0.80	medium, large gravel	no cover

Table 6. Microhabitat cover use for robust redhorse compared to microhabitat availability in the Piedmont and Coastal Plain reaches of the Pee Dee River, North Carolina, South Carolina. Flow ranges are based on the Progress Energy Instream Flow Study (Progress Energy 2006)

Flow range (m^3/s)	Available habitat (*N*)	Microhabitat use (*N*)	X^2	*P*
Piedmont reach				
11 - 102	9,874	476	874.16	<0.0001
108 - 227	11,276	143	974.31	<0.0001
232 - 566	12,695	149	785.53	<0.0001
Coastal Plain reach				
11 - 566	10,248	46	99.645	<0.0001

Table 7. Robust redhorse microhabitat use according to season. Seasons are delineated as spring (March–May), summer (June–September), and winter (October–February). Continuous variables are presented as means, and categorical variables are presented as modes. Unique letters following means and modes indicate significant differences (*P* < 0.05) among seasons for each variable. Continuous variables were analyzed using a Kolmogorov-Smirnov two-sample test while the categorical variable (cover) was analyzed using a likelihood-ratio chi-square test. For substrate and cover abbreviations, see Tables 2 and 3.

Season and sample size (*N*)		Depth (m)	Mean velocity (m/s)	Bottom velocity (m/s)	Temp ˚C	Substrate	Distance to bank (m)	Cover
Spring	Mean or mode	1.9(a)	0.33(a)	0.2(a)	19.54	SD(a)	44.6(a)	BD(a)
N = 376	SE	0.05	0.01	0.01	0.2	0.158	2.68	
	Minimum	0.6	0.01	-0.18	10.1	ST	2.5	
	Maximum	7.0	1.67	2.2	27.5	BR	150.0	
Summer	Mean or mode	2.27(b)	0.18(b)	0.12(b)	27.5	SD(b)	56.3(b)	BD(a)
N = 392	SE	0.05	0.01	0.01	0.08	0.18	1.84	
	Minimum	0.8	-0.03	-0.09	23.9	ST	3.0	
	Maximum	5.2	1.22	0.79	32.1	BR	156.0	
Winter	Mean or mode	2.45(b)	0.13(b)	0.09(b)	10.06	SD(b)	47.7(a)	BD(a)
N = 42	SE	0.14	0.01	0.01	0.48	0.488	5.62	
	Minimum	0.8	0.0	0.0	6.0	ST	9.0	
	Maximum	4.6	0.52	0.62	14.5	BR	133.0	

Table 8. Robust redhorse microhabitat use according to fish sex and season. Seasons correspond to spring (March–May), summer (June–September), and winter (October–February). A Kolmogorov-Smirnov two-sample test was used to test for differences between sexes.

		N		Mean		SE			
Season		Male	Female	Male	Female	Male	Female	*D* statistic	*P*-value
Spring	Mean velocity (m/s)	122	254	0.37	0.34	0.02	0.02	0.15	0.04
	Depth (m)	122	254	1.74	1.99	0.08	0.06	0.14	0.10
	Substrate	122	254	5.09	5.15	0.28	0.18	0.07	0.82
	Dist to bank (m)	122	254	34.3	39.4	2.80	1.99	0.08	0.59
Summer	Mean velocity (m/s)	147	245	0.18	0.18	0.02	0.01	0.06	0.85
	Depth (m)	147	245	2.20	2.30	0.06	0.06	0.09	0.41
	Substrate	147	245	4.82	4.99	0.30	0.23	0.04	1.00
	Dist to bank (m)	147	245	53.2	52.0	3.02	2.23	0.09	0.94
Winter	Mean velocity (m/s)	15	27	0.15	0.12	0.03	0.02	0.19	0.90
	Depth (m)	15	27	2.25	2.57	0.24	0.17	0.44	0.04
	Substrate	15	27	4.13	4.11	0.84	0.61	0.06	1.00
	Dist to bank (m)	15	27	48.1	40.2	10.62	6.14	0.18	0.94

Table 9. Microhabitat use comparison from April 15 to May 15 between 2008 (minimum flow of 11.3 m^3/s) and 2009 (minimum flow of 34.0 m^3/s). Continuous variables were analyzed using a Kolmogorov-Smirnov two-sample test, and cover was analyzed using a likelihood-ratio chi-square test. For substrate and cover abbreviations see Tables 2 and 3.

	N		Mean or mode		SE			
	2008	2009	2008	2009	2008	2009	Statistic	*P*
Depth (m)	97	98	1.82	2.01	0.08	0.10	$D = 0.114$	0.482
Bottom velocity (m/s)	97	98	0.16	0.21	0.02	0.02	$D = 0.786$	<0.0001
Mean velocity (m/s)	97	98	0.28	0.31	0.03	0.02	$D = 0.353$	<0.0001
Distance to bank (m)	97	98	41.6	33.4	3.25	3.00	$D = 2.09$	0.023
Substrate	97	98	vcg	vcg	n/a	n/a	$D = 0.091$	0.820
Cover	97	98	sb	sb	n/a	n/a	$X^2 = 3.451$	0.178

Table 10. Microhabitat use and availability principal component loadings, eigenvalues, and cumulative variance explained for specified flow ranges.

	Flow ranges (m^3/s)							
	11 - 23		28 - 40		56 - 79		158 - 249	
Variable and statistic	PC1	PC 2	PC1	PC 2	PC1	PC 2	PC1	PC 2
Distance to bank (m)	0.64	-0.12	0.63	0.29	0.688	0.102	0.671	0.003
Depth (m)	-0.47	-0.43	0.12	-0.71	-0.087	-0.707	-0.348	-0.002
Mean velocity (m/s)	-0.17	0.89	-0.36	0.61	-0.156	0.698	-0.168	0.967
Substrate	0.58	0.04	0.68	0.18	0.703	-0.033	0.631	0.254
Eigen value	1.53	1.04	1.27	1.15	1.27	1.14	1.36	0.99
Cumulative variance explained (%)	38.30	64.22	31.8	60.7	31.7	60.2	34.2	59.2

Table 11. Statistical comparisons (Kolmogorov-Smirnov two-sample test) of microhabitat use and availability scores for individual components of the flow-specific principal components analysis. Flows 34 m³/s and 68 m³/s were omitted because of low sample sizes.

Flow (m³/s)	Component	*D*-statistic	*P*
17	1	0.531	<0.0001
17	2	0.727	<0.0001
204	1	0.100	0.075
204	2	0.276	<0.0001

Table 12. Depth, bottom and mean velocity, and water temperature for capture locations of robust redhorse during spring of 2008 and 2009 (N = 43).

	Depth (m)		Bottom velocity (m/s)		Mean velocity (m/s)		Water temperature °C	
	2008	2009	2008	2009	2008	2009	2008	2009
Mean	1.15	0.91	0.33	0.39	0.63	0.49	19.9	21.1
SE	0.09	0.06	0.10	0.07	0.06	0.05	0.38	0.14
Minimum	0.64	0.55	0.01	0.06	0.17	0.10	17.5	19.7
Maximum	2.38	1.46	2.20	1.49	1.16	0.96	22.1	22.0

Table 13. Robust redhorse spring capture location dominant substrate percentages among total captures according to year. For substrate sizes, refer to Table 2.

Substrate category	2008 (N = 23)	2009 (N = 20)
Sand	4.3	5.0
Very coarse sand	0	15.0
Fine gravel	13.0	5.0
Medium gravel	13.0	25.0
Coarse gravel	39.1	15.0
Very coarse gravel	13.0	30.0
Small cobble	8.7	0
Large cobble	4.3	5.0
Small boulder	4.3	0

Table 14. Microhabitat comparisons between selected capture locations (Capture) and corresponding grid points surrounding the capture location (Grid). For substrate and cover abbreviations, refer to Tables 2 and 3.

	Depth (m)		Bottom velocity (m/s)		Mean velocity (m/s)		Substrate		Cover	
	Capture	Grid	Capture	Grid	Capture	Grid	Capture	Grid	Capture	Grid
Mean or mode	0.86	0.84	0.41	0.26	0.45	0.61	cg	vcg	nc	nc
SE	5.3	0.34	0.08	0.002	0.05	0.004				
Minimum	0.55	0.0	0.06	-0.27	0.09	-0.29	vcs	st	mb	ev
Maximum	1.15	1.53	1.49	1.12	0.88	1.44	vcg	br	cwd	vlb

Table 15. Robust redhorse seasonal and annual linear range for resident and migratory subgroups of robust redhorse in the Pee Dee River, North Carolina and South Carolina. Seasons correspond to spring (March–May), summer (June–September), and winter (October–February).

Season	Subgroup	*N*	Mean (km)	Median (km)	SE (km)	Min – max (km)
Annual	Resident	621	9.8	10.2	1.4	0.2 – 26.0
	Migratory	193	91.8	106.6	9.5	52.1 – 114.2
	Combined	814	30.2	12.1	6.6	0.19 – 114.2
Spring	Resident	278	10.2	9.1	2.1	0.2 – 40.0
	Migratory	91	47.8	31.5	14.9	5.1 – 106.9
	Combined	359	19.6	10.0	5.0	0.17 – 106.9
Summer	Resident	321	8.1	5.5	1.8	0.2 – 36.4
	Migratory	94	45.3	49.9	13.5	2.6 – 91.9
	Combined	407	17.3	6.2	4.5	0.15 – 91.9
Winter	Resident	36	3.8	2.3	1.2	0.0 – 15.4
	Migratory	12	18.5	6.4	10.8	0.0 – 57.1
	Combined	48	7.7	2.3	3.1	0 – 57.1

Table 16. Seasonal and annual directional (i.e., upstream or downstream) movements for robust redhorse in the Pee Dee River, North Carolina, South Carolina.

Season	Direction	Number of relocations	Mean (km)	Median (km)	SE (km)	Min – max (km)
Annual	Upstream	373	1.8	0.5	0.3	0.01 – 57.22
	Downstream	396	2.6	0.6	0.4	0.01 – 91.62
Spring	Upstream	171	2.6	0.7	0.5	0.01 – 57.22
	Downstream	181	2.4	0.6	0.4	0.01 – 58.45
Summer	Upstream	180	0.93	0.2	0.16	0.01 – 15.31
	Downstream	201	2.93	0.5	0.75	0.01 – 91.62
Winter	Upstream	22	3.5	1.5	1.2	0.01 – 26.78
	Downstream	14	1.4	0.7	0.5	0.14 – 6.49

Table 17. Mean, median, standard error, linear range and kernel density estimates for robust redhorse with at least 30 relocations (N = 14 fish) according to behavioral subgroup in the Pee Dee River. Linear range is the distance spanned among relocations for individual fish. Kernel density estimates for the 99%, 95%, 90%, and 50% levels represent utilization distributions at that specified percentage.

Parameter	Linear home range (km)	Kernel density (km)			
		99%	95%	90%	50%
All fish					
Mean	24.0	12.1	7.4	5.4	1.3
Median	10.4	4.6	3.5	3.1	0.8
SE	7.4	3.8	2.2	1.5	0.4
Minimum	2.6	2.0	1.8	1.3	0.4
Maximum	79.1	48.8	27.6	17.4	7.0
Resident subgroup					
Mean	7.9	4.7	4.0	3.1	0.8
Median	7.3	3.7	3.1	2.3	0.7
SE	3.7	3.2	2.6	2.1	0.4
Minimum	2.6	2.0	1.8	1.3	0.4
Maximum	3.6	11.6	8.9	6.7	1.4
Migratory subgroup					
Mean	64.3	30.7	15.9	11.1	2.5
Median	68.9	31.1	17.0	12.9	1.1
SE	8.4	7.5	5.6	3.7	1.5
Minimum	40.3	11.8	2.1	1.4	0.8
Maximum	79.1	48.8	27.6	17.4	7.0

Table 18. Linear ranges and kernel density estimates for individual robust redhorse with at least 30 relocations according to resident or migratory subgroup (N = 14). Linear range is the distance spanned among relocations for individual fish. Kernel density estimates for the 99%, 95%, 90%, and 50% levels represent utilization distributions at that specified percentage. Six fish had multiple core areas at the 50% level.

Transmitter frequency	Linear range (km)	Kernel density (km)				Core areas	
		99%	95%	90%	50%	1	2
			Resident				
40.021	11.2	4.7	3.5	3.5	0.7		
40.061	5.9	4.6	3.4	2.6	0.7		
40.841	6.5	2.9	2.7	1.7	0.4		
41.682	12.2	9.2	8.6	6.7	1.4		
41.720	2.6	2.0	1.9	1.3	0.5		
40.540	3.9	2.7	1.8	1.4	0.5	0.40	0.10
40.690	13.6	11.6	8.9	6.6	1.3	0.30	0.81
40.761	9.6	4.5	4.3	3.9	1.0	0.90	0.10
40.800	4.9	2.3	1.8	1.5	0.4	0.10	0.30
41.660	8.1	2.8	2.8	2.0	0.8	0.80	0.20
			Migratory				
40.611	40.3	32.0	27.6	17.4	7.0	6.50	0.50
40.671	79.1	48.8	2.1	1.4	0.8		
40.730	68.8	30.3	22.3	16.7	0.9		
41.741	69.0	11.8	11.8	9.1	1.3		

Table 19. Fish size comparisons of resident and migratory robust redhorse behavioral subgroups. Variables were compared using a Student's t-test.

	Resident	Migratory	*t*	*P*
Total length (mm)				
N	7	31	0.72	0.49
Mean	652.5	669.8		
SE	22.6	7.9		
Weight (g)				
N	7	31	-0.13	0.89
Mean	4,423.9	4,346.6		
SE	561	183.4		

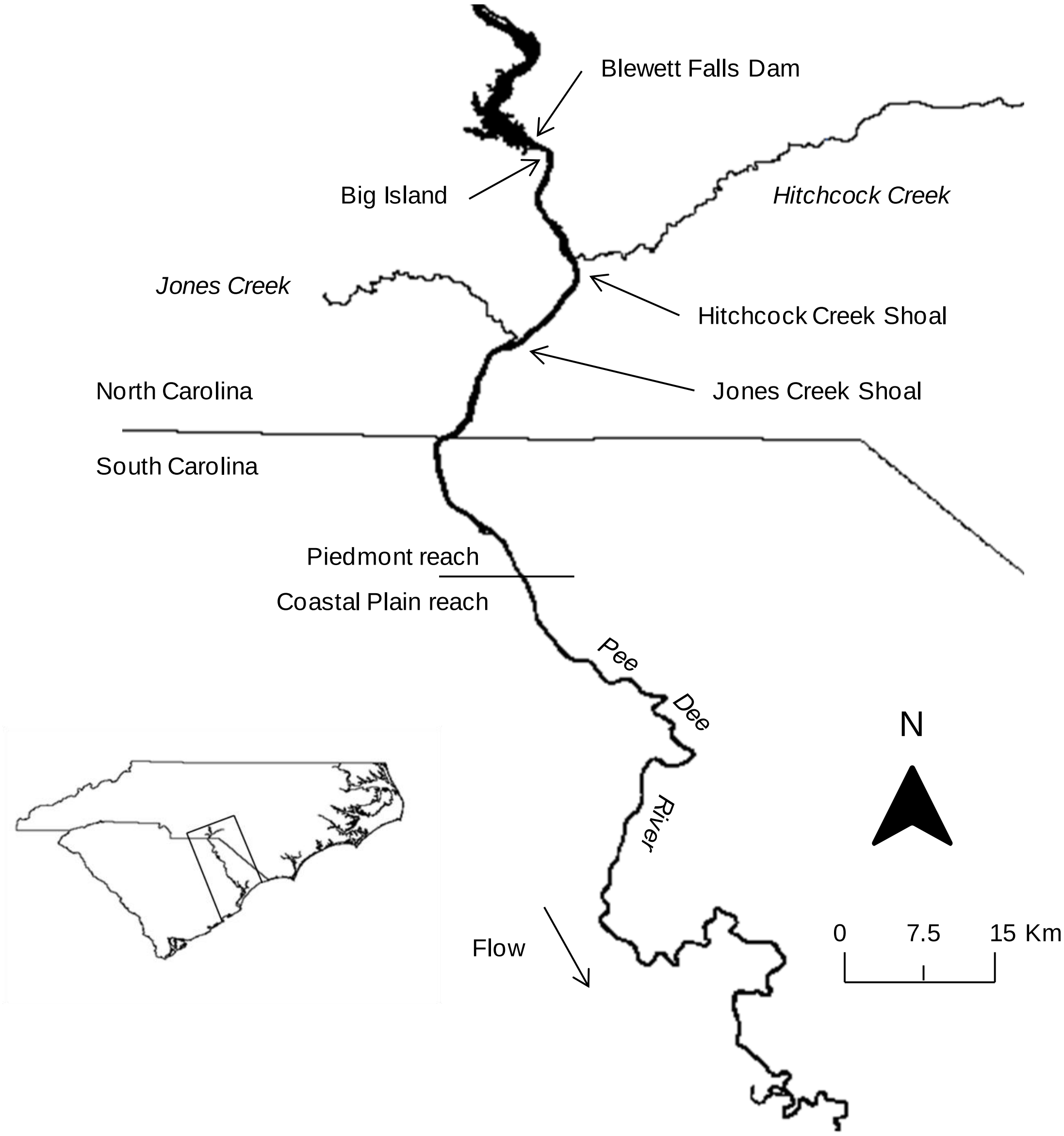

Figure 1. Map of the study area on the Pee Dee River, North Carolina and South Carolina.

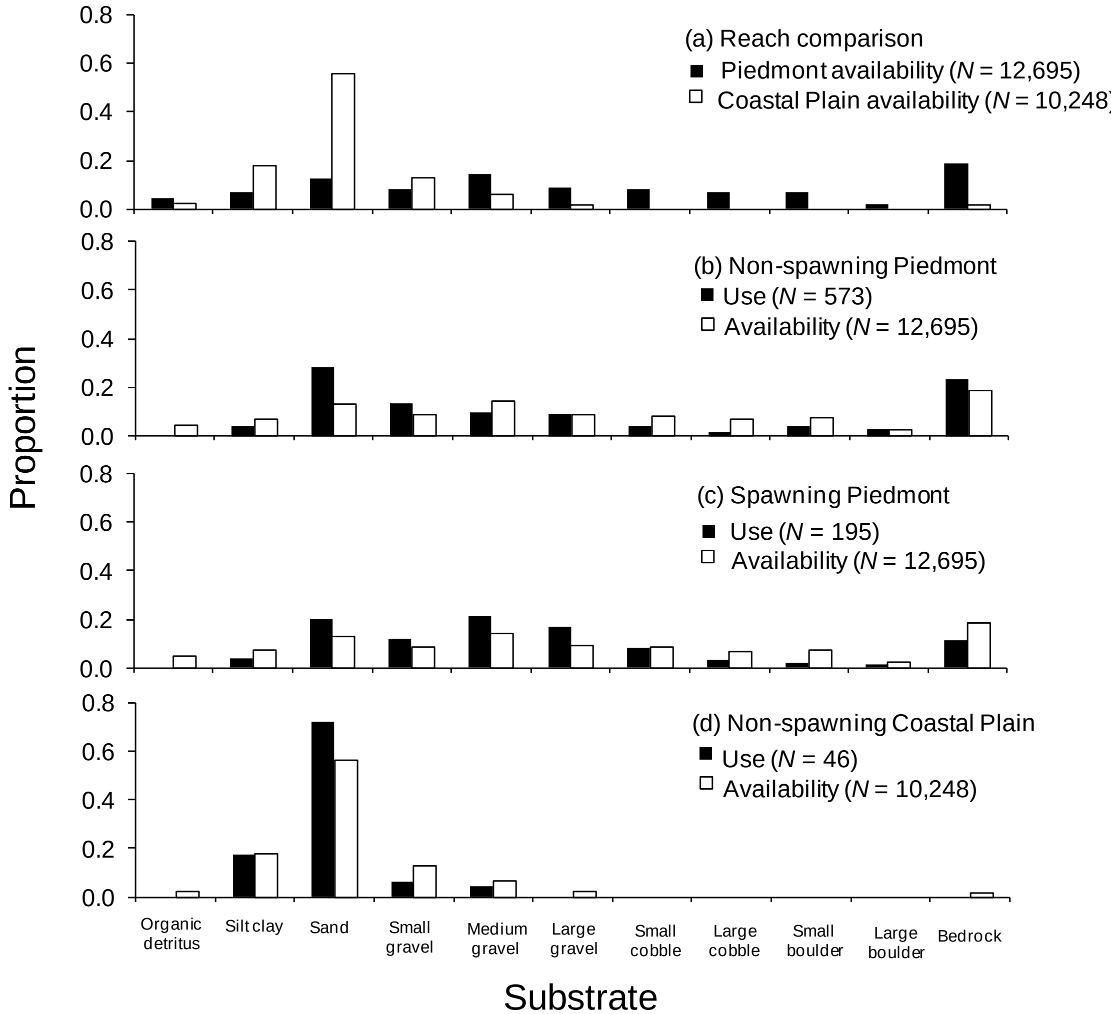

Figure 2. Frequency distributions for (a) Piedmont and Coastal Plain microhabitat availability, (b) non-spawning Piedmont, (c) spawning Piedmont, and (d) non-spawning Coastal Plain robust redhorse substrate microhabitat use and availability for the Pee Dee River, North Carolina, South Carolina. Substrate proportions are combined from habitat analyses from multiple flows.

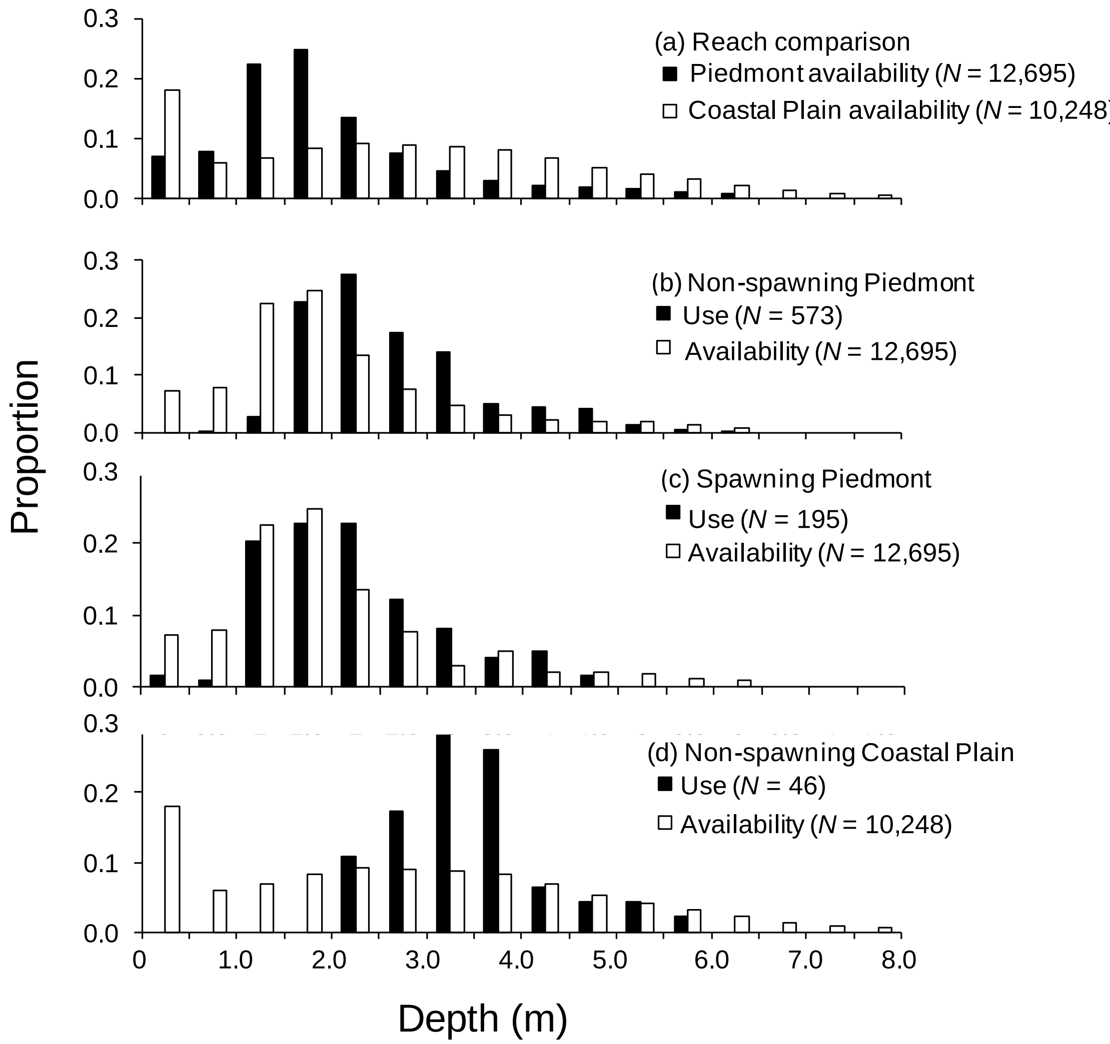

Figure 3. Frequency distributions of (a) Piedmont and Coastal Plain microhabitat availability, (b) non-spawning Piedmont, (c) spawning Piedmont, and (d) non-spawning Coastal Plain robust redhorse microhabitat use and availability for depth in the Pee Dee River, North Carolina, South Carolina. Depth proportions are combined from habitat analyses from multiple flows.

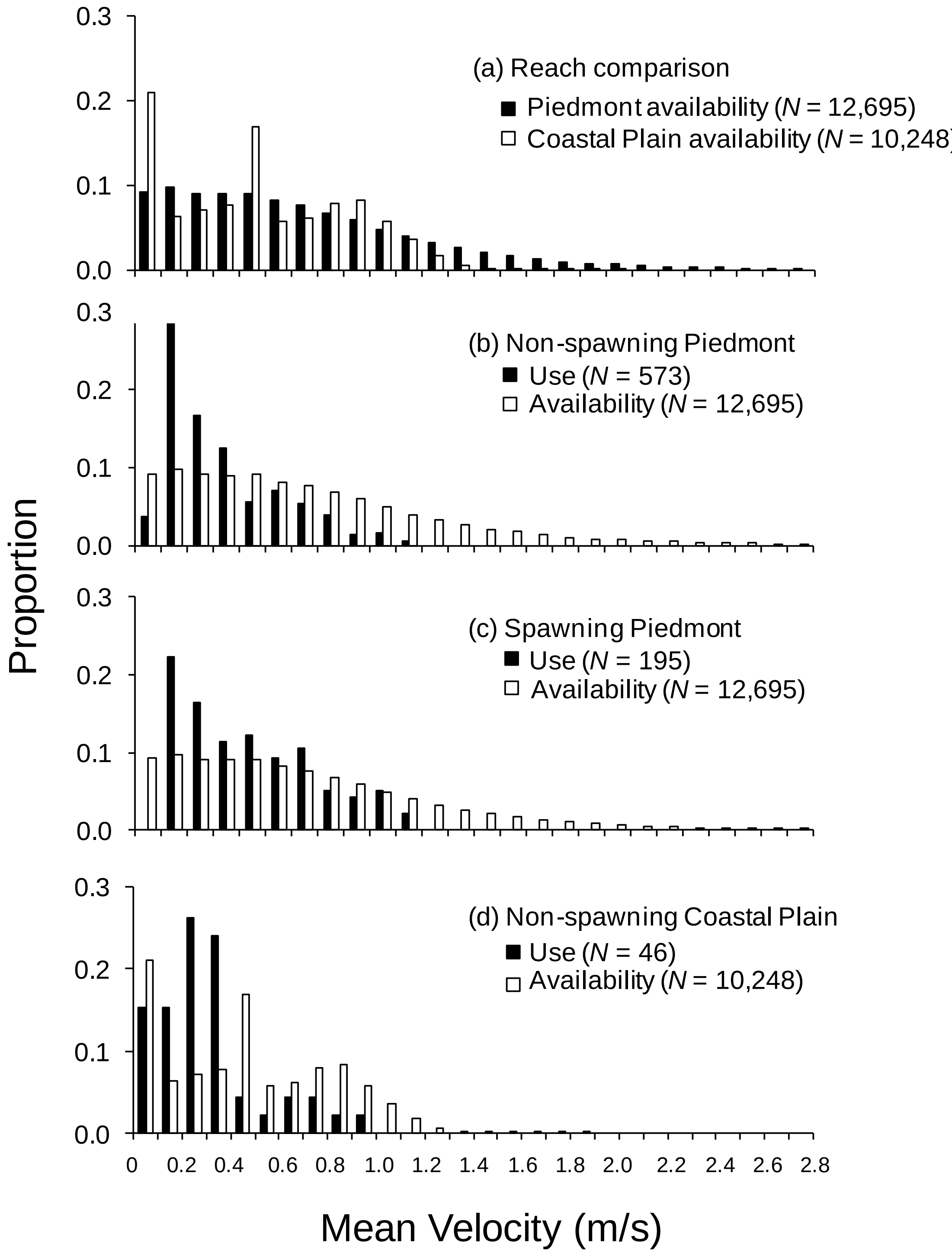

Figure 4. Frequency distributions for (a) Piedmont and Coastal Plain microhabitat availability, (b) non-spawning Piedmont, (c) spawning Piedmont, and (d) non-spawning Coastal Plain robust redhorse mean velocity microhabitat use and availability for the Pee Dee River, North Carolina, South Carolina. Mean velocity proportions are combined from habitat analyses from multiple flows.

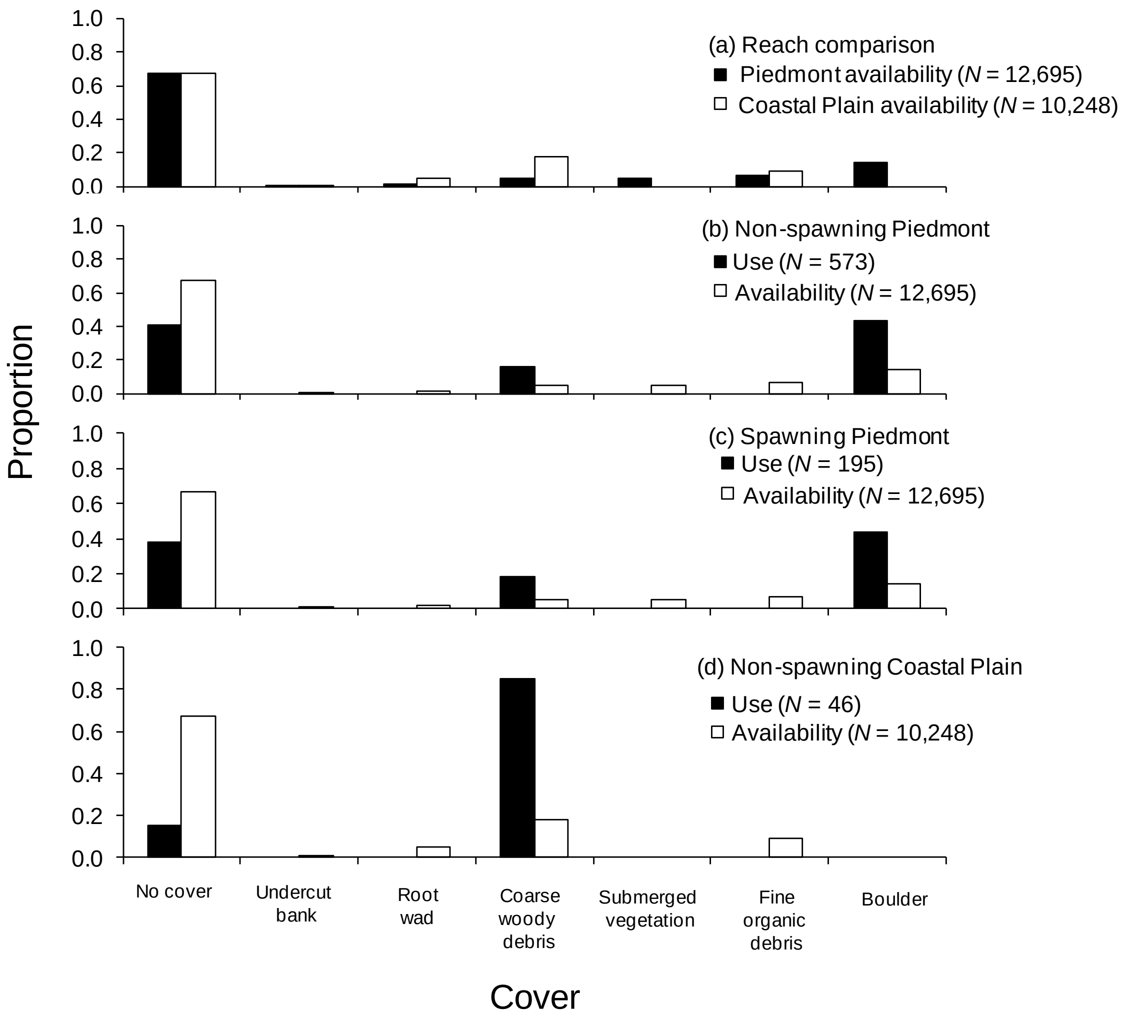

Figure 5. Frequency distributions for (a) Piedmont and Coastal Plain microhabitat availability, (b) non-spawning Piedmont, (c) spawning Piedmont, and (d) non-spawning Coastal Plain robust redhorse cover microhabitat use and availability for the Pee Dee River, North Carolina, South Carolina. Cover proportions are combined from habitat analyses from multiple flows.

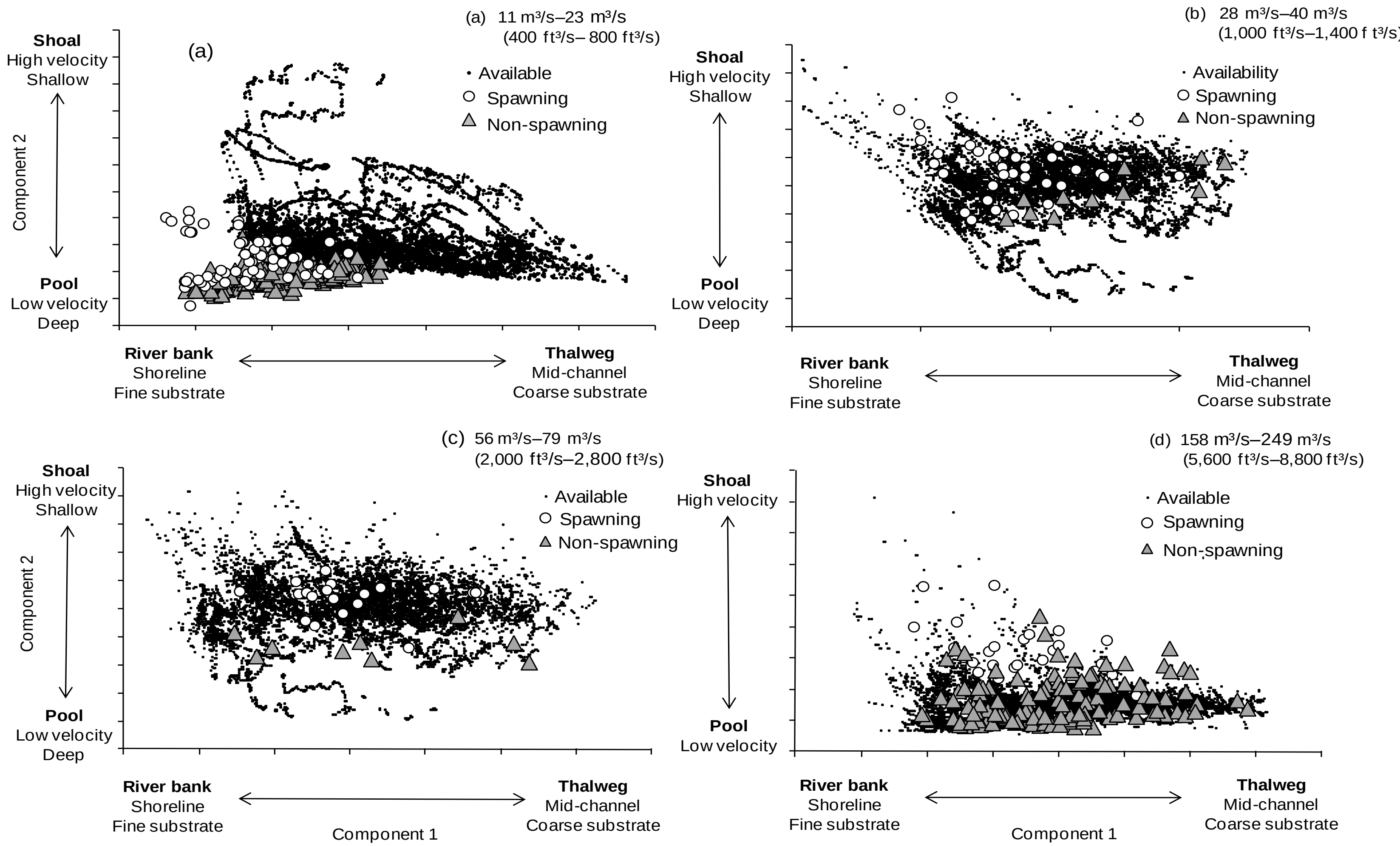

Figure 6. Plots of robust redhorse microhabitats used and available principal component scores under varying flow ranges (a-d) in the Pee Dee River, North Carolina, South Carolina. Principal component loadings appear in Table 10.

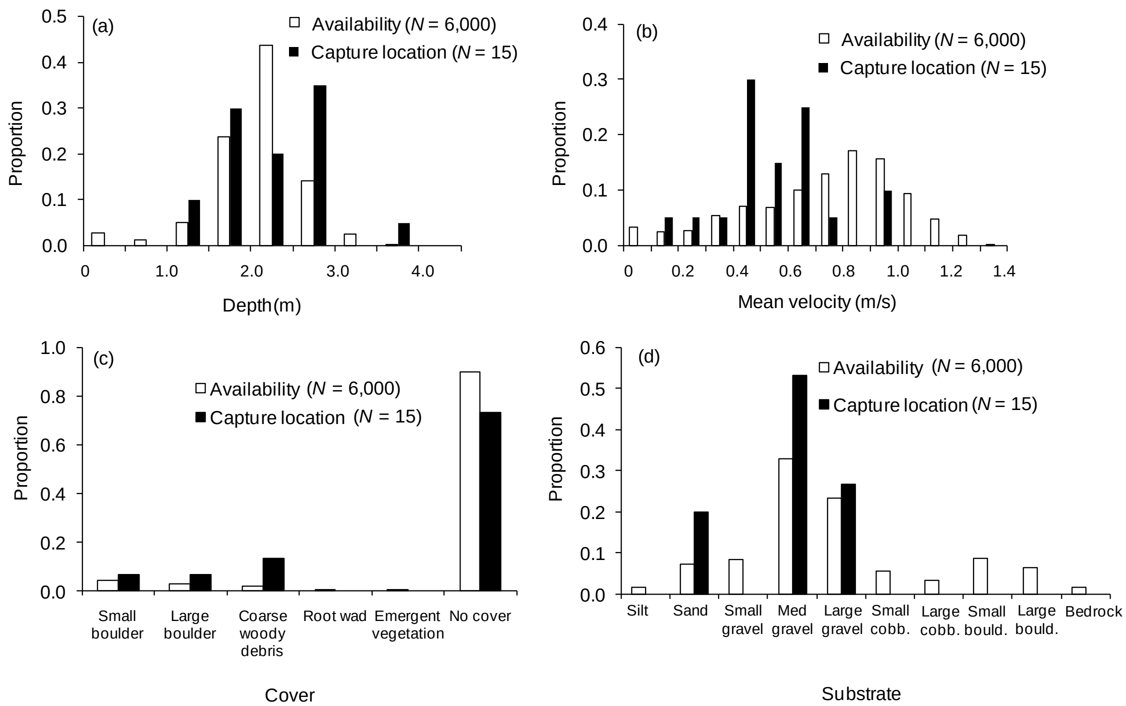

Figure 7. Spawning microhabitat use and availability distributions for (a) depth, (b) mean column velocity, (c) cover, and (d) substrate for selected 2009 robust redhorse capture locations and associated capture grids.

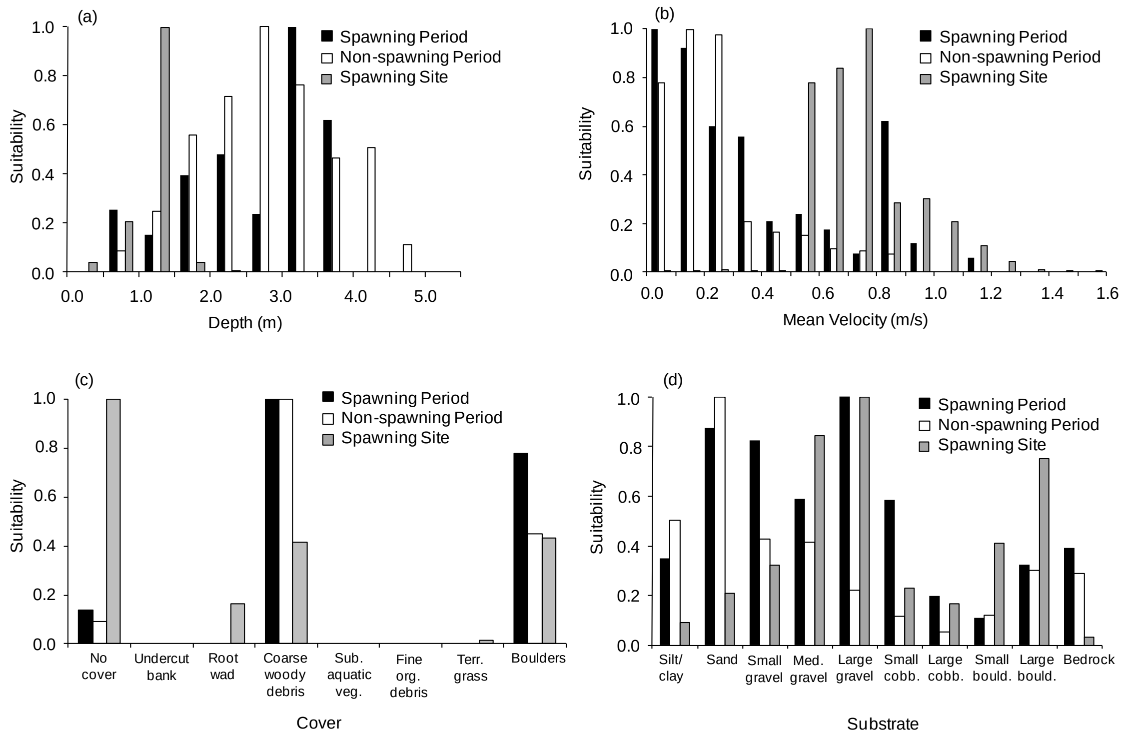

Figure 8. Robust redhorse spawning period, non-spawning period, and spawning site suitability for (a) depth, (b) mean column velocity, (c) cover, and (c) substrate for the Pee Dee River, North Carolina and South Carolina, based on telemetry relocations and capture locations.

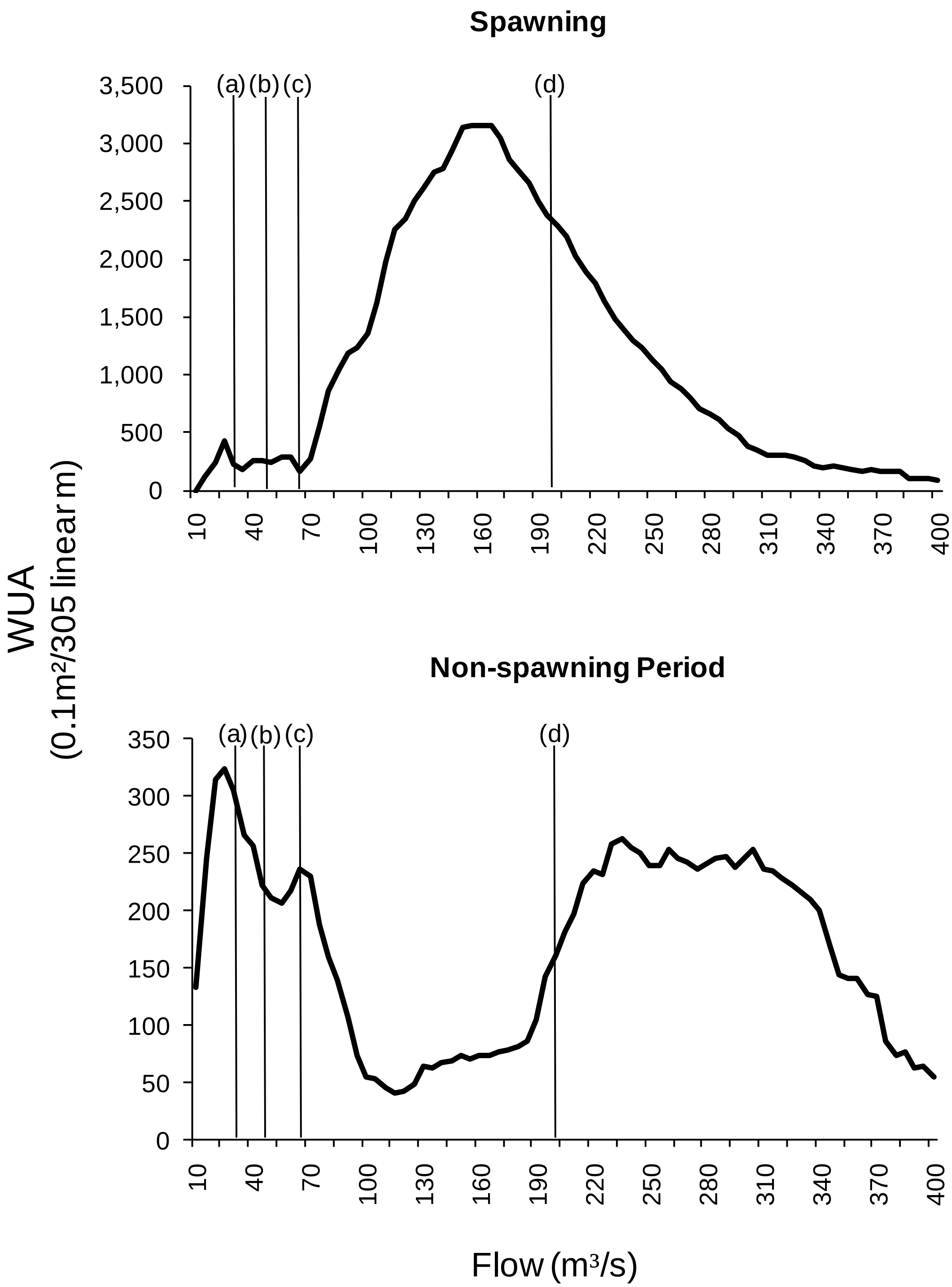

Figure 9. Weighted usable area for robust redhorse spawning and non-spawning habitat. Letters correspond to (a) 34 m^3/s (1,200 ft^3/s), (b) 51 m^3/s (1,800 ft^3/s), (c) 68 m^3/s (2,400 ft^3/s) proposed minimum flows for Blewett Falls Dam, and (d) the peak efficiency flow (~204 m^3/s, 7,200 ft^3/s).

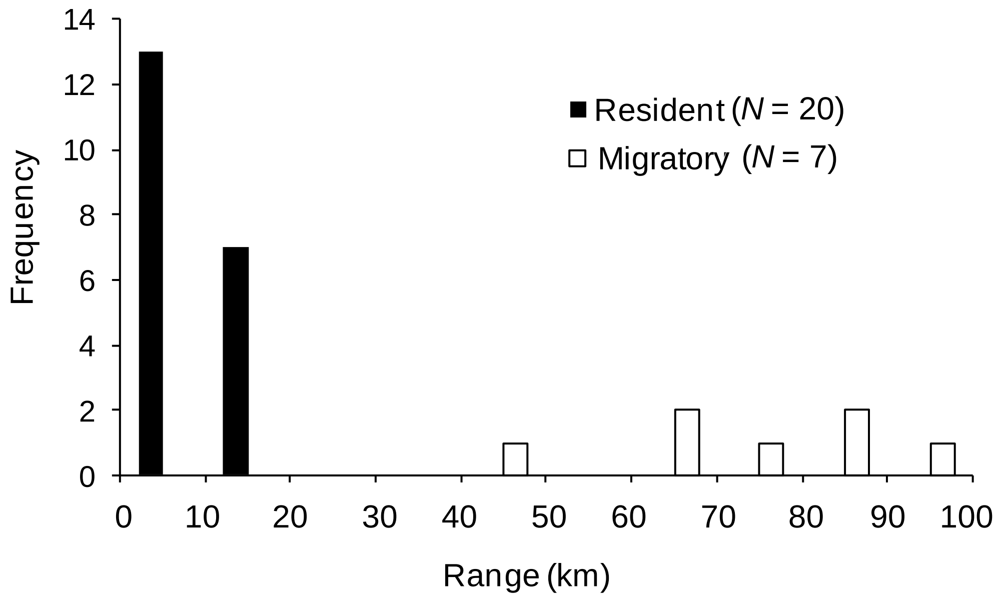

Figure 10. Linear ranges of robust redhorse in the Pee Dee River, North Carolina and South Carolina. Robust redhorse are separated into behavioral subgroups.

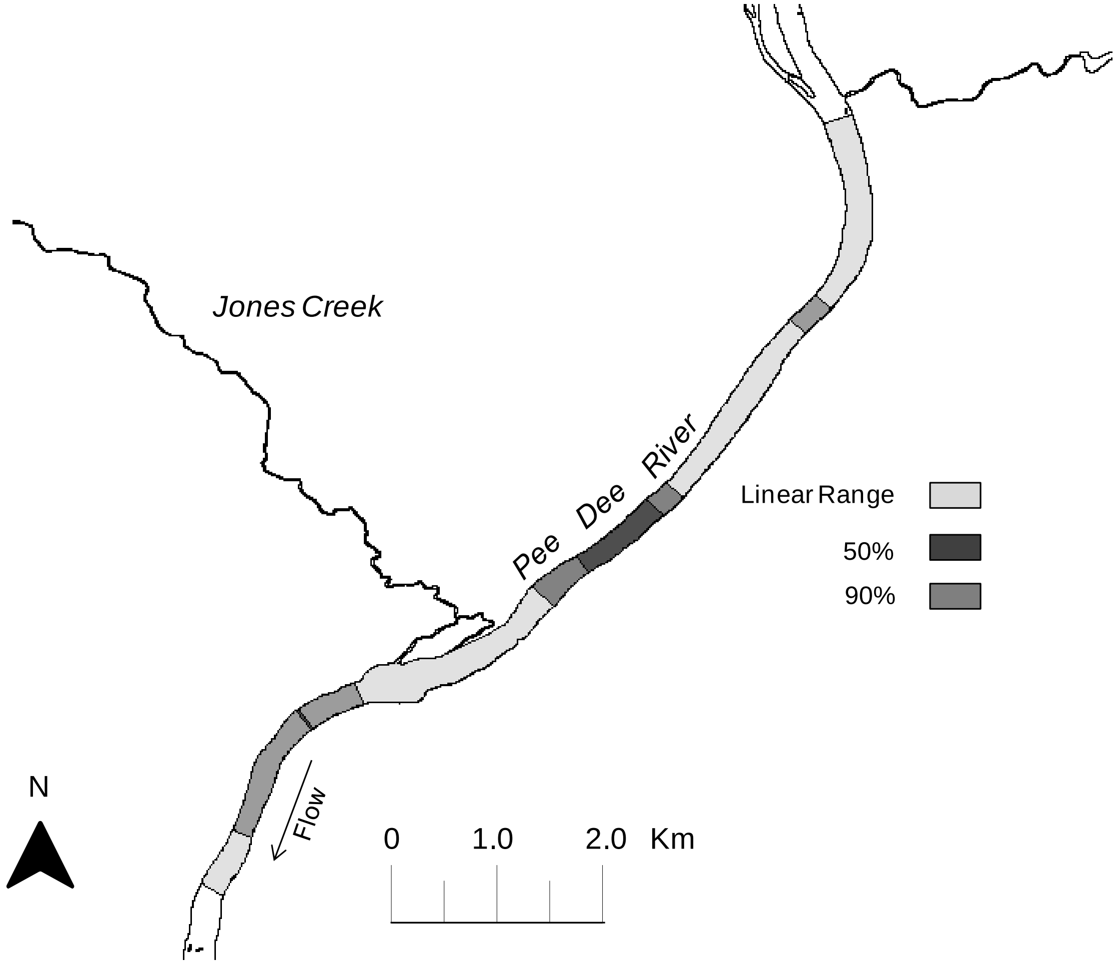

Figure 11. Mapped example of linear range, 50%, and 90% kernel density estimates for robust redhorse transmitter frequency 40.761 in the Pee Dee River, North Carolina

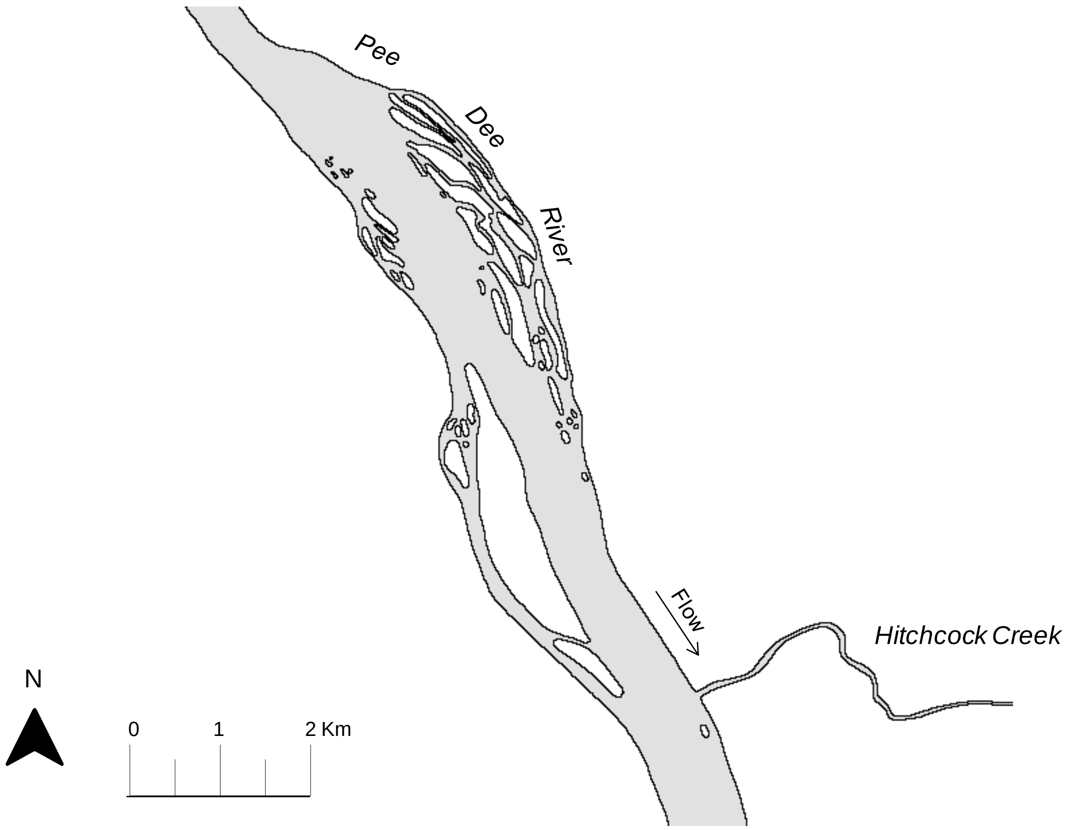

Figure 12. Map of Hitchcock Creek Shoal and associated side channels. Robust redhorse utilize the main western side channel as well as the margin of the main channel to spawn.

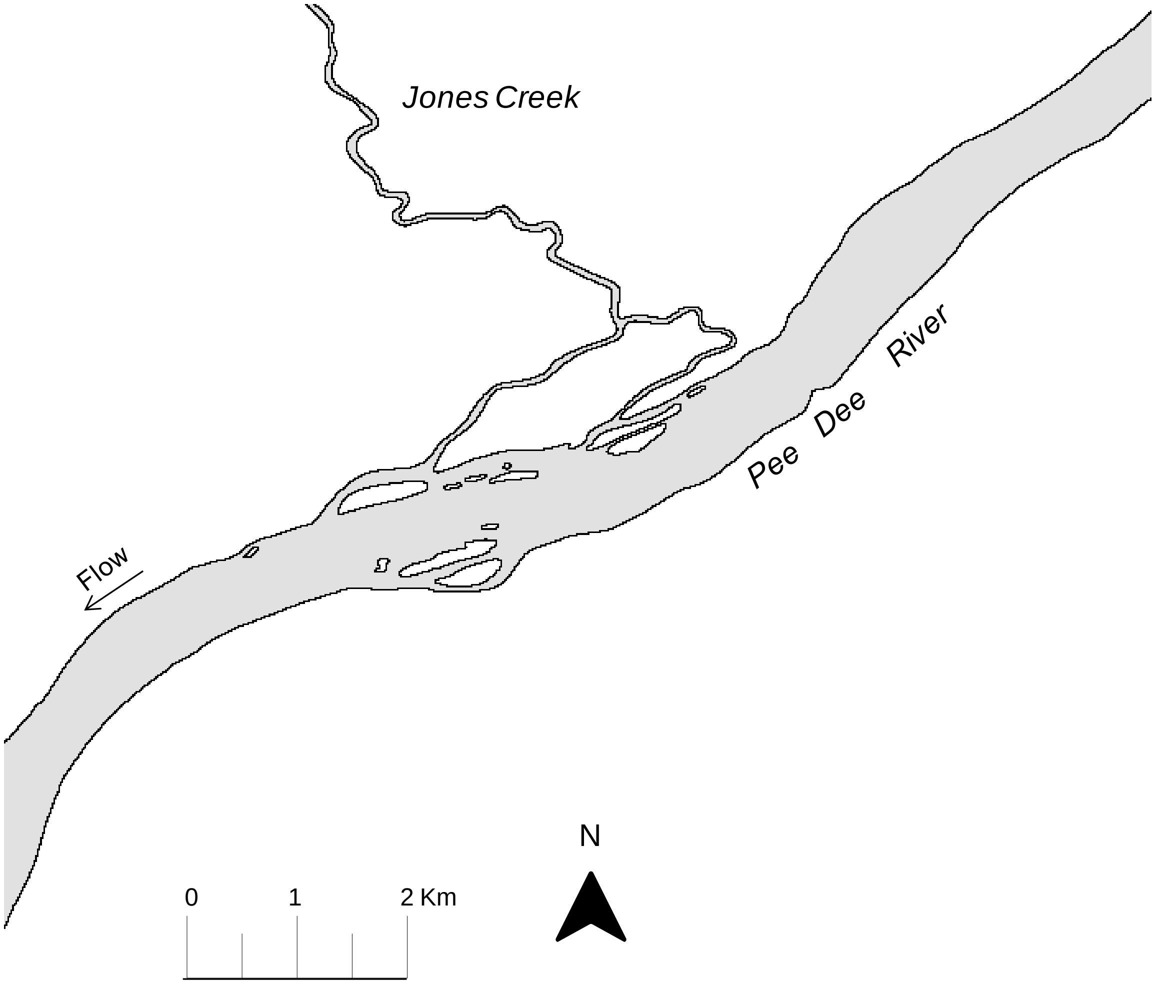

Figure 13. Map of Jones Creek Shoal and associated side channels. Robust redhorse utilize both eastern and western side channels as well as the margins of the main channel to spawn.

Chapter II ─ Effects of Redd Dewatering on Hatching and Larval Survival of the Robust Redhorse

Abstract

Riverine habitats have been altered and fragmented from hydroelectric dams. These habitats change spatially and temporally, dependent on flow releases coinciding with hydropower production. Hydropeaking flow regimes inundate areas to create temporary suitable habitat for fish that may be rapidly drained. Robust redhorse *Moxostoma robustum* an imperiled, rare fish species, utilizes these temporary habitats to spawn but when power generation ceases, these areas are dewatered until the next pulse of water is released. I investigated the effects of dewatering periods on the survival of robust redhorse eggs and larvae. Robust redhorse eggs were placed in gravel in eyeing-hatching jars (3 jars per treatment) and subjected to one of four dewatering periods (6 h, 12 h, 24 h, and 48 h), followed by 12 h of inundation for each treatment, and a control treatment was never dewatered. Egg desiccation was observed in some eggs in the 24- and 48-h treatments after one dewatering period but eggs hatched in these treatments on day 7 post-fertilization. By day 9, all visible eggs hatched. For all treatments except the control, after eggs hatched, the subsequent dewatering period was lethal. Larval emergence for the control treatment was observed on day 5 post-hatching and continued until the end of the experiment. At the end of the experiment, 108 larvae were collected in the control treatment gravel and none in any other treatment gravel. Additional larvae were found below the mesh screen and filter apparatus including 34 larvae in the control, 0 in the 6-h, and 4, 3, and 2 in the 12-h, 24-h, and 48-h treatments respectively. Larval survival was significantly different among treatments when individuals in the gravel were included, but when larvae collected below the mesh screen were also included in the analysis, only the control and 6-h treatment were significantly different. These findings support the need for hydropower facilities to set

minimum flows to maintain inundation of spawning areas for robust redhorse and other species to reduce mortality from dewatering.

Introduction

The construction and operation of dams fragment and alter the natural flow of over half of the world's major rivers (Dynesius and Nilsson 1994; Nilsson et al. 2005). In the United States, the Yellowstone River is the only river over 1,000 km that has not been severely altered for hydropower, flood control, and navigation (Benke 1990). Dams cut off migratory routes for fishes including access to spawning habitats (Baxter 1977; Lucas and Baras 2001), and available habitats downstream are dependent on either dam spillage or hydropower discharge (Poff et al. 1997; Bowen et al. 1998). These downstream habitats can be altered spatially and temporally (Freeman et al. 2001) and have led to changes in fish communities (Pringle et al. 2000; Bunn and Arthington 2002; Quinn and Kwak 2003). Hydropeaking power generation is a method used to meet short-term electricity demands that requires a large pulse of water released in a short time period that creates large fluctuations in available habitats (Freeman et al. 2001). The regularity and duration of hydropeaking is dependent on electrical power demands of the hydropower facility and typically result in multiple peaks per day to once every other day.

Fluctuations from hydropeaking can inundate areas with water and create temporary suitable habitats that can be exploited for foraging, cover, or reproduction. The biological consequences of utilizing these temporary habitats can be risky. Juvenile Atlantic salmon *Salmo salar*, Chinook salmon *Oncorhynchus tshawytscha*, and brown trout *Salmo trutta trutta* that use these habitats are vulnerable to becoming stranded and isolated from the main river channel in pools, leading to high mortality (Hvidsten 1985; Bradford 1997; Saltveit et al. 2001). Lithophilic spawning fish that utilize these habitats to deposit demersal eggs in the substrate are subjected to periodic dewatering as a result of hydropeaking operation. These fish include catostomids, cyprinids, and salmonids among others (Breder and Rosen 1966).

Redd dewatering has been documented in Kokanee salmon *Oncorhynchus nerka*, (Stober and Tyler 1982), Chinook salmon (McMichael et al. 2005), quinnant salmon *Oncorhynchus tshawytscha* (Hawke 1978), brown trout, and steelhead trout *Oncorhynchus mykiss* (Becker and Neitzel 1985), rainbow trout, *Oncorhynchus mykiss* (Becker et al. 1985; Pender and Kwak 2002), and recently documented on the Savannah River, Georgia, South Carolina for the robust redhorse (Grabowski and Isely 2007). The effects of redd dewatering have primarily been studied in salmonids in western U. S. rivers. Several studies have shown that salmon eggs are resilient to dewatering for periods up to 5 weeks as long as they were kept moist, did not freeze, or temperatures did not exceed incubation tolerances (Reiser and White 1981; Reiser and White 1983; Becker et al. 1985; McMichael et al. 2005). Salmon eggs are tolerant of dewatering under experimental and natural conditions, but mortality increases significantly when eggs hatch and larvae are dependent on gills for respiration (Becker et al. 1982; Stober and Tyle 1982; Becker et al. 1983; Reiser and White 1983).

Thus, I initiated a laboratory experiment to simulate the effects of dewatering on robust redhorse fertilized eggs and larvae. Since dewatered robust redhorse redds have been found in the Savannah River, Georgia, South Carolina (Grabowski and Isely 2007) and observed anecdotally in the Pee Dee River, North Carolina (Ryan Heise, North Carolina Wildlife Resources Commission, personal communication; author's personal observations), knowledge of these effects is vital to the conservation and long-term survival of this species. Further, the hydro-regulated flow regimes of all three drainages where robust redhorse are found warrants such a study. These findings will also improve understanding of the effects of redd dewatering on fish eggs and larvae in southeastern warmwater systems, the most diverse and vulnerable fish fauna in the U.S. (Jelks et al. 2008).

Methods

Laboratory Setup

The experiment was conducted indoors at the McKinney Lake State Fish Hatchery near Hoffman, North Carolina. Fifteen 14.2-L eyeing-hatching jars (Eager, Inc.) were used for experimental replicates. Each cylindrical jar was 30.5 cm in diameter with a height of 66 cm. These hatching jars have been used by the South Carolina Department of Natural Resources to hatch and rear fertilized robust redhorse as a component of a state stocking program. The hatching jars have a hemispherical bottom to facilitate hatching by creating upwelling that diffuses through the 20-mm thick random nylon mesh mat filter. This ensures adequate water movement over the eggs for aeration and to remove waste with minimal flow. Robust redhorse eggs can successfully hatch in an aquarium environment with minimal flow (< 3.8 L/min), so long as water flows around them (Forrest Sessions, South Carolina Department of Natural Resources, personal communication). These jars were assembled with water piped in through the bottom and flowing out of the top from the pour spout that drains into a common reservoir. Water was then forced through a Hayward S310S sand filter with a Hayward 0.75-horsepower Super Pump. This precaution was to prevent the introduction of Savannah River strain robust redhorse into the Pee Dee River drainage, because the hatchery effluent ultimately drained into a tributary of the Pee Dee River.

Groups of three hatching jars were designated to one of four dewatering treatments (6 h, 12 h, 24 h, and 48 h) that mimicked hydropeaking conditions in the Pee Dee River and other drainages and a control treatment that was never dewatered. When the treatment jars were not dewatered, water flowed through them for 12 h until the cycle was repeated. All treatments were initiated with 12 h of inundation followed by their prescribed treatment. Gravel similar to spawning substrate used by robust redhorse described by Freeman and Freeman (2001) was placed in each jar 5 cm deep. This was placed on a nylon mesh diffusing mat that was supported by an aluminum coned perforated screen that allowed for uniform upwelling and served as a medium upon which the eggs were placed.

Eggs were obtained on May 6, 2009, from wild Savannah River, Georgia, South Carolina, brood stock at river km 283, (16 rkm downstream of the New Savannah Bluff Lock and Dam). One female was stripped, and eggs were divided into three equal groups. Three males were stripped to fertilize one group of eggs, and then all three groups were combined again and taken to Bayless Striped Bass Hatchery, Saint Stephen, South Carolina. Fertilized eggs were transported to McKinney Lake State Fish Hatchery the same day. Each treatment jar was stocked with 100 eggs, and each control treatment jar contained 250 eggs. Eggs were not treated with formalin or any other prophylactic treatment solution throughout the experiment. Eggs were distributed with a glass siphon throughout the gravel and settled into interstitial spaces between the gravel with some eggs resting on top of the gravel. I used hatchery well water that was pumped through an aeration system that oxygenates and denitrogenates it before being stored in a water tower for later use.

Four Claber® (Aquano Video 6) automatic water timers controlled each treatment water flow and were programmed with water flowing for 12 h and then turned off for the specified time of each treatment automatically. Each treatment hatching jar had an outflow of at least 3.8 L/min. Each treatment was piped together using 3.8-cm polyvinyl chloride

(PVC) main pipe. After flowing out of the water timer, each treatment pipe split off the main pipe to the appropriate hatching jar. After branching off to the appropriate hatching jar, the main pipe for each treatment continued underneath the last hatching jar and was oriented into the common reservoir and controlled with a ball valve on the terminal end. The main pipe and terminal ball valve were at a lower elevation than all three jars for each treatment to facilitate draining when water timers shut off at the beginning of a dewatering cycle. The terminal ball valve for each treatment was adjusted to constantly drain so that when a water timer shuts off, all three hatching jars for that treatment drain and become dewatered for the specified time. The jars for each treatment drained completely in 20-25 min. The outflow volume from the terminal ball valve was less than the inflow from the water timer, to allow the hatching jars to fill and overflow automatically.

After the initial dewatering period for each treatment, and following reinundation, some of the eggs lost their adhesiveness and were elevated by water surface tension. To prevent eggs from flowing up and out of each jar, a fiberglass screen was placed 5 cm below the pour spout of each hatching jar. As eggs came into contact with the screen, water continued to fill the jar and any eggs would fall into the gravel substrate.

The experiment was initiated at 12 AM on May 7, 2009, and monitored twice daily, approximately every 12 h. Any physical development or behavior was recorded. Dissolved oxygen (mg/L) and temperature (°C) were measured throughout the experiment. Once distributed into the substrate, egg number and fate could not be precisely quantified at any given time, but larvae observed swimming out of the gravel were captured with an aquarium net and preserved in 5% buffered formalin. To compensate for restricted time to observe and collect emerging larvae, as well as their tendency to emerge at night (Clifford 1972; Muth and Schmulbach 1984; D'Amours et al. 2001), a modified aquarium net was placed onto the pour spout of each jar to collect any emerging larvae that may be caught in the outflow current. Total length (mm) was recorded for all robust redhorse larvae captured. At the termination of the experiment, all gravel was carefully removed and any larvae remaining in each hatching jar were preserved. Additional larvae were collected below the nylon mesh and aluminum screen at the termination of the experiment and were included in analysis.

Statistical Analyses

Differences in larval survival at the end of the experiment among experimental groups were analyzed for larvae collected in gravel and below the nylon mesh. Larvae that emerged throughout the experiment were excluded in this analysis because they were removed and subsequently not subjected to additional dewatering periods. Larval survival data did not conform to a normal distribution and the condition was not improved with an arcsin transformation (Zar 1996). Thus, a Kruskal-Wallis test was used to detect significant differences among experimental groups. A Nemenyi multiple comparison test was used to detect pairwise differences between treatments (SAS 2010). To test if robust redhorse larvae emerge at a specific length, simple regression was used to analyze the relationship between larval emergence day and total length. Larvae that appeared deformed were excluded (N = 12).

Results

Mean water temperature during the experiment was 18.65 °C (SE 0.21 °C, range 16.97-20.22 °C, N = 21) with mean dissolved oxygen of 10.28 mg/L (SE 0.24 mg/L, range 8.95–10.99 mg/L, N = 10). After the initial 12 h of inundation the treatments began their dewatering cycles. When dewatered, eggs in the gravel were difficult to observe, but some that were on top of the gravel were dried out by the end of the first cycle of the 24- and 48-h treatments. By day 7 post-fertilization, all observed eggs in the control and 6-h treatment had visible eye spots, and movement was observed inside the control treatment. One egg out of seven (14.3%) observed in the 12-h treatment had an eye spot. At the same time, hatched larvae were observed in the 24-h treatment (N = 5) and 48-h treatment (N = 1) on the substrate surface with no other eggs observed in the 24-h treatment and some dried eggs on the substrate surface in the 48-h treatment. By eight days after fertilization, most eggs in the control treatment hatched (17 observed not hatched), and all visible eggs in the 6-h treatment hatched and were down in the substrate. No eggs or larvae were observed in any other treatment. All visible eggs were hatched and down in the substrate by nine days after fertilization for the control and 6-h treatment. Once hatched, many of the larvae observed were oriented in a vertical position with their heads toward the mesh filter. By 10 days after fertilization, only the larvae in the control treatment jars were visible, and no eggs or larvae were observed in any treatment throughout the rest of the experiment.

Emergent larvae were collected beginning 12 days after fertilization (5 days post hatching) to the end of the experiment (Table 1). All larvae were caught in the nets attached to the pour spouts, suggesting they were suspended or swam out of the jars, except for five caught by hand. Typically when an observer approached the jars, larvae that were swimming up in the water column retreated into the substrate. This fleeing behavior was also observed from larvae in the substrate that were observed on the perimeter of jars; those larvae moved into the center of the jar through interstitial spaces. Larval emergence peaked over two days (6-7 days post-hatching) and decreased significantly by day 11 post-hatching. A total of 93 larvae were collected, 77 (83%) in the morning (night emergence) and 16 (17%) in the evening (day emergence) (Table 2).

Upon conclusion of the experiment on May 28, 2009 (after day 21), a total of 108 live larvae were found, all in the control treatment. No larvae were collected from the gravel in all of the treatments. After removing the gravel, the nylon mesh and perforated aluminum screen was removed and unexpectedly, additional live robust redhorse larvae were found primarily in the control treatment with a few from the 12-h, 24-h, and 48-h treatments (Table 2). This finding of additional larvae below the screen and filter also indicated that larvae had direct access through the terminal ball valve into the common reservoir, and seven additional larvae were collected there.

Larval survival in the control was significantly different ($P < 0.01$) from all treatments, based on collections from the gravel substrate (Table 2). When larvae collected below the mesh filter were included in the analysis. A marginally significant difference ($P = 0.0515$) was detected so a Nemenyi multiple comparison test was used to detect differences between pairs. Larval survival in the control treatment was significantly different than the 6-h treatment, but all other comparisons were not significantly different (Table 2).

There was a positive relationship between day of emergence and total length (Figure 1) that indicated that larvae did not emerge at a specific length but continued to grow and emerge throughout the experiment. Yolk sacs were present on 29 (31%) of the emerged larvae, and six (4%) contained some amount of yolk sac at the end of the experiment. The mean total length for all larvae caught was 12.75 mm (SE = 0.079 mm).

Discussion

Robust redhorse eggs can withstand some degree of dewatering, but once hatched, dewatering for six hours or longer was lethal. This is similar to findings in salmonid studies where salmon eggs have the ability to survive dewatered conditions, but when larvae become dependent on gills for respiration, mortality increases significantly (Becker et al. 1982; Stober and Tyle 1982; Becker et al. 1983; Reiser and White 1983). Ambient moisture and humidity can play an important role in egg survival. The few eggs that were on the substrate surface became desiccated in dewatering periods of 12 h or more. Under natural conditions, these eggs would likely be pushed down into the substrate by flow or be preyed upon if they remained on the gravel surface, and such egg desiccation may be rare.

Water temperature was not controlled in the experiment and fluctuated several degrees according to daily air temperatures. Water was pumped from a well but was stored in an elevated water tank until used, which buffered the range of temperature fluctuation. Water temperatures in my experiment (17–22 °C) were slightly cooler than temperatures normally used (20–22 °C) to hatch out robust redhorse in hatchery conditions (Forrest Sessions, South Carolina Department of Natural Resources, personal communication). Robust redhorse usually hatch in 4-6 days, but hatched in the control jars on days 8 and 9. The 24-h and 48-h treatments hatched on day 7, and the 6-h treatment on day 8. The dewatering period seemed to accelerate development, likely from the warmer ambient air temperature and the treatments with the longest dewatering period hatched earlier. Reiser and White (1983) also found that steelhead and Chinook salmon eggs subjected dewatering hatched earlier than those continually immersed. Faster development could benefit larvae if density dependent factors such as the availability of interstitial gravel space or food are limited. However, if redd temperatures (wet or dry) exceed thermal tolerance limits for developing eggs, then mortality could increase substantially. The effects of direct sunlight were not addressed in my experiment, as it was conducted in a building that prevented such exposure. In natural conditions, redd temperature fluctuations could vary much greater than what occurred (17–20 °C) in my experiment. Along with accelerating critical thermal limits, direct sunlight may reduce intergravel moisture and lead to egg desiccation, as I observed in this experiment. Exposure to ultraviolet B (UVB) radiation from sunlight may have other detrimental effects on eggs as well. Northern Anchovy *Engraulis mordox* eggs and larvae exposed to UVB levels similar to natural sunlight suffered 100% mortality (Vetter et al. 1999) and a negative correlation between UVB levels and embryonic survival for Atlantic cod *Gadus morhua* has also been found (Kuhn et al. 2000). Water filters out UVB radiation, and if redds are dewatered, then exposure may increase significantly.

Larval escapement was an unforeseen outcome of this experiment. Larvae were able to penetrate below the mesh filter and aluminum screen and survive for at least 48 h in the small amount of residual water after treatment jars were drained. This may have implications on the fate of larvae in the substrate that becomes dewatered. Once dependent on gill respiration, larvae in dewatered jars suffered 100% mortality. My observations and those of Weyers et al. (2003) found that larvae can stay in the substrate from 5–10 days before emerging, leaving them vulnerable to multiple dewatering events. My observations and those of Weyers et al. (2003) also found that robust redhorse larvae can move freely through the interstitial space of gravel, provided adequate space. Garcia de Leaniz et al. (1993) found that larval salmon migrate laterally through the gravel before emerging. This behavioral strategy may also apply to robust redhorse larvae to allow migration without vertical movement up into the water column, which would risk predation but is dependent on the availability of interstitial space in the gravel. If the interstitial space in the gravel is filled to impede movement (e.g., by sedimentation), this behavior would not be possible, and alternatives remain unknown.

In a hydro-regulated river setting, larvae that locate residual water in the substrate and survive after dewatering may be trapped until the next release of water. This could result in delays of physical and developmental processes. If the duration of the dewatering period results in anoxic conditions, high mortality may result. In addition to dissolved oxygen concerns, larval fish need to migrate to the water surface and gasp air to initiate the inflation of their air bladders and delaying or failure to complete this process has been linked to decreased survival (Egloff 1996; Martin-Robichaud and Peterson 1998).

After initial dewatering cycles, some eggs lost their adhesiveness and were suspended by the surface tension of the rising water in the hatching jars. These eggs were captured in the pour spout nets and then manually redistributed into the substrate. Robust redhorse eggs are demersal, only slightly adhesive and probably rely on being deposited down in the substrate where they adhere to the substrate or are held there by flowing water. If a redd is dewatered, then inundated again, eggs could potentially be removed from the substrate and swept downstream into less suitable habitat or preyed upon while up in the water column. Even though eggs can tolerate some amount of dewatering this could ultimately lead to increased mortality. This observation (suspended eggs) has not been noted in other such lab studies and may be unique to the robust redhorse or *Moxostoma* in general.

Larval robust redhorse do not emerge at a specific length but continually grow and emerge in response to other physical or chemical cues. A similar pattern is known for salmon (McMichael et al. 2005) and sturgeon (Braaten et al. 2008). Emergence is probably related to energetic needs as yolk sacs are absorbed. Yolk sacs were absent in 69% of emerged larvae. Although emergence was not related to length it displayed a diel pattern with most larval robust redhorse emerging at night (77%). This behavior has been found in other catostomids (Clifford 1972; Muth and Schmulbach 1984) and is likely a mechanism to avoid visual predators (Iguchi and Mizuno 1990; Flecker et al. 1991).

Differences in survival were clearly evident between the control and all other treatments. No larvae in any treatment survived in the gravel and none emerged throughout the duration of the experiment. After hatching, no larvae were observed in any treatment after the following dewatering period, and because of this, it is uncertain when some larvae escaped through the mesh filter. When eggs hatched, almost all larvae observed were oriented vertically with their head facing the mesh filter; this is most likely the time they escaped through the filter. The percentage of larvae of each group found below the mesh and screen were low: control (3%), 6-h (0%), 12-h (1%), 24-h (3%), and 48-h (1%). As larvae grew throughout the experiment it would be increasingly difficult to pass through the mesh filter and screen. Thus, I consider that the larvae escaped through the mesh screen at a similarly low rate among groups. Under natural conditions, migration from the original hatching location would be expected at least from a small proportion of larvae (Garcia de Leaniz et al. 1993).

When the larvae below the mesh screen were included in the analyses to detect differences in survival, the experiment-wide result was marginally significant ($P = 0.0515$) and only the control and 6-h treatment were significantly different. The 95% confidence interval for the control treatment overlapped the 12-h, 24-h, and 48-h treatments due to the large variation in survival of the three control replicates. Confidence intervals would likely be narrowed with a larger sample size, and significant differences would be detected.

My results suggest that survival of robust redhorse eggs and larvae can be enhanced with the proper management of minimum flows to keep spawning gravel bars inundated. My personal observations throughout the study reach during periods at the three proposed minimum flows for the Pee Dee River (Chapter 1), as well as modeled estimates (Progress Energy 2006) demonstrate that all main channel and side channel gravel bars in the Piedmont reach downstream of Blewett Falls Dam would be inundated. This would clearly benefit robust redhorse eggs but most importantly the larvae in these gravel bars. Other species would benefit from higher water surface elevations during the spawning period as well. Grabowski and Isely (2007) observed notchlip redhorse *Moxostoma collapsum*, spotted sucker *Minytrema melanops*, and a carpsucker species *Carpiodes* sp., utilizing the same gravel bars for spawning as those by robust redhorse in the Savannah River, Georgia, South Carolina. Other *Moxostoma* species occur sympatrically with robust redhorse including the undescribed Carolina redhorse *Moxostoma* sp. in the same areas where robust redhorse spawn in the Pee Dee River. Other less conspicuous species such as cyprinids may also use these same habitats for spawning or other functions and could benefit as well.

This study contributes to a better understanding of the basic ecology of robust redhorse early life stages and their tolerance to fluctuating environmental conditions. To my knowledge, the only other studies of the effects of redd dewatering heretofore were on salmon and trout. Salmon dewatering usually occurs in fall spawning fish, where eggs over winter in the substrate. Salmon eggs appear more resilient, as they have to endure colder temperatures and significantly longer incubation and larval intragravel periods (up to seven months for Chinook salmon; McMichael et al. 2005). In contrast, robust redhorse eggs incubate for only 4-6 days, hatch, and emerge in 5-10 days. The temporal opportunity for dewatering is small when compared to species that incubate over winter, but is no less critical, as my results show that even relatively brief periods (6 h) of dewatering can be lethal for larvae.

Habitat loss is considered the greatest threat to imperiled fauna in the United States (Wilcove et al. 1998) including fish (Jelks et al., 2008). Regulated rivers are dramatically altered ecosystems that present challenges to optimize habitat management. Critical habitats can be altered on a daily basis (e.g., hydropeaking) that can strongly impact fishes and other biota. Hydropower facilities have the ability to manage at fine time scales for critical periods (e.g., spawning and egg/larval development) for imperiled species. By enhancing spawning habitats for the robust redhorse, other species are likely to benefit. Fish communities have responded to minimum flows, with increased species diversity and abundance (Travnichek et al. 1995; Lamouroux et al. 2006). This is likely related to access to newly available habitats, but may also be a result of successful recruitment from areas that previously were dewatered. A concept that goes beyond the minimum flow regime is the environmental flow regime (Poff et al 1997; Puckridge et al. 1998; Richter et al. 1998; Pringle et al. 2000; Lytle and Poff 2004). Such flows mimic the timing, duration, and magnitude of unimpeded rivers that coincide with critical time periods of aquatic organisms. Although studies to quantify these effects are limited, experimental environmental flows have resulted in increases in spawning activity in some systems (King et al. 1998; King 2009).

Although FERC relicensing for Blewett Falls Dam is presently unresolved, flow conditions in the Pee Dee River, North Carolina and South Carolina, will improve once new augmented minimum flows are implemented. Other hydro-regulated rivers where robust redhorse and other species are subjected to redd dewatering exist and could benefit from augmented flows that inundate important habitats during critical time periods.

Literature Cited

Baxter, R. M. 1977. Environmental effects of dams and impoundments. Annual Review of Ecology and Systematics 8:255–283.

Becker, C. D., D. A. Neitzel, and D. H. Fickeisen. 1982. Effects of dewatering on chinook salmon redds: tolerance of four developmental phases to daily dewaterings. Transactions of the American Fisheries Society 111:624–637.

Becker, C. D., D. A. Neitzel, and C. S. Abernethy. 1983. Effects of dewatering on chinook salmon redds: tolerance of four developmental phases to one-time dewatering. North American Journal of Fisheries Management 3:373–382.

Becker, C. D., and D. A. Neitzel. 1985. Assessment of intergravel conditions influencing egg and alevin survival during salmonid redd dewatering. Environmental Biology of Fishes 12:33–46.

Becker, C. D., D. A. Neitzel, and D. W. Carlile. 1985. Survival data for dewatered rainbow trout *Salmo gairdneri* eggs and alevins. Journal of Applied Ichthyology 2:102–110.

Benke, A. C. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society 9:77–88.

Bowen, Z. H., M. C. Freeman, and K. D. Bovee. 1998. Evaluation of generalized habitat criteria for assessing impacts of altered flow regimes on warmwater fishes. Transactions of the American Fisheries Society 127:455–468.

Braaten, P. J., D. B. Fuller, L. D. Holte, R. D. Lott, W. Viste, T. F. Brandt, and R. G. Legare. 2008. Drift dynamics of larval pallid sturgeon and shovelnose sturgeon in a natural side channel of the upper Missouri River, Montana. North American Journal of Fisheries Management 28:808–826.

Bradford, M. J. 1997. An experimental study of stranding of juvenile salmonids on gravel bars and in side channels during rapid flow decreases. Regulated Rivers: Research and Management 13:395–401.

Breder, C. M., Jr., and D. E. Rosen. 1966. Modes of reproduction in fishes. Natural History Press, Garden City, New York.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492–507.

Clifford, H. F. 1972. Downstream movements of white sucker, *Catostomus commersoni*, fry in a brown-water stream of Alberta. Journal of the Fisheries Research Board of Canada 29:1091–1093.

D'Amours, J., S. Thibodeau, and R. Fortin. 2001. Comparison of lake sturgeon, *Acipenser fulvescens*, *Stizostedion* spp., *Catostomus* spp., *Moxostoma* spp., quillback, *Carpiodes cyprinus*, and mooneye, *Hiodon tergisus* larval drift in Des Prairies River, Quebec. Canadian Journal of Zoology 79:1472–1489.

Dynesius, M., and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753–762.

Egloff, M. 1996. Failure of swim bladder inflation of perch, *Perca fluviatilis* L. found in natural populations. Aquatic Sciences 58:15–23.

Flecker, A. S., D. C. Taphorn, J. A. Lovell, and B. P. Feifarek, 1991. Drift of characin larvae, *Bryconamericus deuterodonides* during the dry season from Andean piedmont streams. Environmental Biology of Fishes 31:197–202.

Freeman, B. J., and M. C. Freeman. 2001. Criteria for suitable spawning habitat for the robust redhorse *Moxostoma robustum*. U.S. Fish and Wildlife Service Report. Athens, Georgia.

Freeman, M. C., Z. H. Bowen, K. D. Bovee, and E. R. Irwin. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecological Applications 11:179–190.

Garcia de Leaniz, C., N. Fraser, and F. Huntingford. 1993. Dispersal of Atlantic salmon fry from a natural redd: evidence for undergravel movements? Canadian Journal of Zoology 71:1454–1457.

Grabowski, T. B., and J. J. Isely. 2007. Spatial and temporal segregation of spawning habitat by catostomids in the Savannah River, Georgia and South Carolina, USA. Journal of Fish Biology 70:782–798.

Hawke, S. P. 1978. Stranded redds of quinnat salmon in the Mathias River, South Island. New Zealand Journal of Marine and Freshwater Research 12:167–171.

Hvidsten, N. 1985. Mortality of pre-smolt Atlantic salmon, *Salmo salar* L., and brown trout, *Salmo trutta* L., caused by fluctuating water levels in the regulated river Nidelva, central Norway. Journal of Fish Biology 27:711–718.

Iguchi, K., and N. Mizuno, 1990. Diel changes of larval drift among amphidromous gobies in Japan, especially *Rhinogobius brunneus*. Journal of Fish Biology 37: 255–264.

Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Díaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren, Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33(8):372–407.

King, A. J., Z. Tonkin, and J. Mahoney. 2009. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. River Research and Applications 25:1205–1218.

King, J., J. A. Cambray, N. D. Impson. 1998. Linked effects of dam-released floods and water temperature on spawning of the clanwilliam yellowfish *Barbus capensis*. Hydrobiologia 384:245–265.

Kuhn, P. S., H. I. Browman, R. F. Davis, J. J. Cullen, and B. L McArthur. 2000. Modeling the effects of ultraviolet radiation on embryos of *Calanus finmarchicus* and Atlantic cod *Gadus morhua* in a mixing environment. Limnology and Oceanography 45:1797–1806.

Lamouroux, N. J., M. Oliver, H. Capra, M. Zylberblat, A. Chandesris, and P. Roger. 2006. Fish community changes after minimum flow increase: testing quantitative predictions in the Rhone River at Pierre-Benite, France. Freshwater Biology 51:1730–1743.

Lucas, M. C., and E. Baras. 2001. Migration of freshwater fishes. Blackwell Science. Ames, Iowa.

Lytle, D. A., and L. N. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19:94–100.

Martin-Robichaud, D. J., and R. H. Peterson. 1998. Effects of light intensity, tank colour, and photoperiod on swimbladder inflation success in larval striped bass, *Morone saxatilis* (Walbaum). Aquaculture Research 29:539–547.

McMichael, G. A., C. L. Rakowski, B. B. James, and J. A. Lukas. 2005. Estimated fall Chinook salmon survival to emergence in dewatered redds in a shallow side channel of the Columbia River. North American Journal of Fisheries Management 25:876–884.

Muth, R. T., and J. C. Schmulbach. 1984. Downstream transport of fish larvae in a shallow prairie river. Transactions of the American Fisheries Society 113:224–230.

Nilsson, C., C. A. Reidy, M. Dynesius, and C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. Science 308:405–408.

Pender, D. R., and T. J. Kwak. 2002. Factors influencing brown trout reproductive success in Ozark tailwater rivers. Transactions of the American Fisheries Society 131:698–717.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47:769–784.

Pringle, C. M., M. C. Freeman, and B. J. Freeman. 2000. Regional effect of hydrologic alterations on riverine macrobiota in the New World: tropical-temperate comparisons. Bioscience 50:807–823.

Progress Energy. 2006. Application for license: Yadkin-Pee Dee River project, FERC No. 2206. Progress Energy, Raleigh, North Carolina.

Puckridge, J. T., F. Sheldon, K. F. Walker, and A. J. Boulton. 1998. Flow variability and the ecology of large rivers. Marine and Freshwater Research 49:55–72.

Quinn J. W., and T. J. Kwak. 2003. Fish assemblage change in an Ozark river after impoundment: a long-term perspective. Transactions of the American Fisheries Society 132:110–119.

Reiser, D. W., and R. G. White. 1981. Incubation of steelhead trout and spring chinook salmon eggs in a moist environment. The Progressive Fish-Culturist 43:131–134.

Reiser, D. W., and R. G. White. 1983. Effects of complete redd dewatering on salmonid egg-hatching success and development of juveniles. Transactions of the American Fisheries Society 112:532–540.

Richter, B. D., D. P. Braun, M. A. Mendelson, and L. L. Master. 1998. Threats to imperiled freshwater fauna. Conservation Biology 11:1081–1093.

Saltveit, S., J. Halleraker, J. Arnekleiv, and A. Harby. 2001. Field experiments on stranding in juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) during rapid flow decreases caused by hydropeaking. Regulated Rivers: Research and Management 17:609–622.

Stober, Q. J., and R. W. Tyler. 1982. Rule curve for irrigation drawdown and kokanee salmon (*Oncorhynchus nerka*) egg to fry survival. Fisheries Research 1:195–218.

Travnichek, V. H., M. B. Bain, and M. J. Maceina. 1995. Recovery of a warmwater fish assemblage after the initiation of a minimum flow release downstream from a hydroelectric dam. Transactions of the American Fisheries Society 124:836–844.

Vetter, R. D., A. Kurtzman, and T. Mori. 1999. Diel cycles of DNA damage and repair in eggs and larvae of northern anchovy, *Engraulis mordox*, exposed to solar ultraviolet radiation. Photochemistry and Photobiology 69:27–33.

Weyers, R. S., C. A. Jennings, and M. C. Freeman. 2003. Effects of pulsed, high-velocity water flow on larval robust redhorse and v-lip redhorse. Transactions of the American Fisheries Society 132:84–91.

Wilcove, D. S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. BioScience 48:607–615.

Zar, J. H. 1996. Biostatistical analysis, 3rd edition. Prentice-Hall Inc., Upper Saddle River, New Jersey.

Table 1. Numbers of emerged larval robust redhorse collected according to day post-hatching. Table headings Night and Day refer to periods when larvae emerged. All emerged larvae were collected from control replicate jars; no larvae emerged from any dewatering treatments.

Day (post-hatching)	Night	Day	Total
5	1	0	1
6	13	7	20
7	14	4	18
8	9	1	10
9	11	2	14
10	11	1	12
11	15	0	15
12	1	0	1
13	1	0	1
14	1	0	1
Total	77	16	93

Table 2. Larval survival according to treatment at experiment termination (day 21). Larvae from the common reservoir ($N = 7$) were omitted from analysis. Means followed by the same letter are not significantly different ($P > 0.05$).

Treatment	Larvae collected from gravel	Larvae collected below filter	Means among replicates of larvae collected in gravel	SE	Means among replicates of larvae from gravel plus larvae collected below filter	SE
Control	108	34	21.64(a)	0.05	43(a)	9.23
6 hour	0	0	0(b)	0	0(b)	0
12 hour	0	4	0(b)	0	1.33(ab)	0.88
24 hour	0	3	0(b)	0	2.66(ab)	2.19
48 hour	0	2	0(b)	0	0.66(ab)	0.33
Total	108	50				

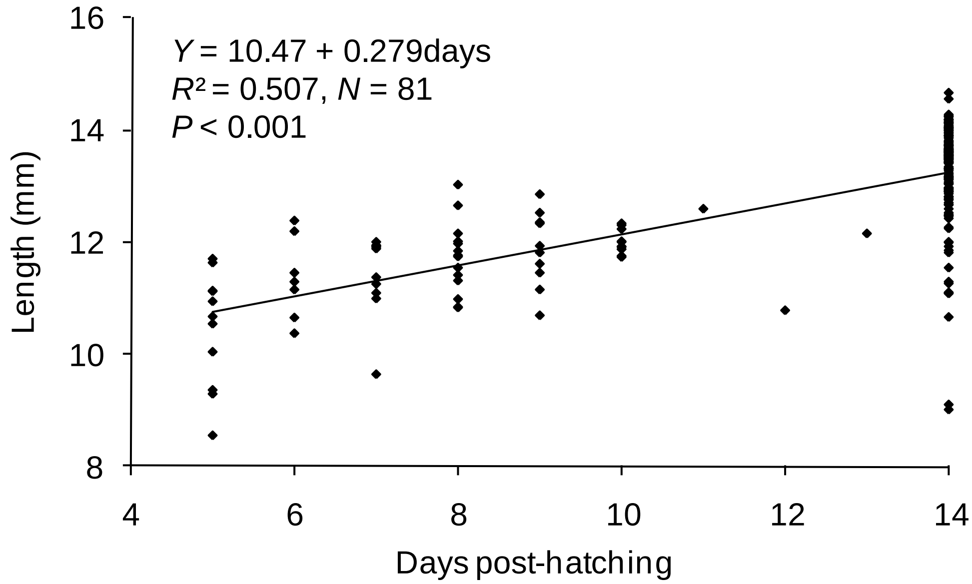

Figure 1. Total length of emerged larval robust redhorse by day (post-hatching). Larvae collected that appeared deformed (*N* = 12) were excluded.