ABSTRACT

RAABE, JOSHUA KENT. Factors Influencing Distribution and Survival of Migratory Fishes Following Multiple Low-Head Dam Removals on a North Carolina River. (Under the direction of Dr. Joseph E. Hightower).

Migratory fish species are assumed to benefit from dam removals that restore connectivity and access to upstream habitat, but few studies have evaluated this assumption. Therefore, I assessed factors influencing distribution and survival of migratory fishes in the springs of 2007 through 2010 on the Little River, North Carolina, a tributary to the Neuse River with one partial and three complete dam removals. I tagged migratory fishes with passive integrated transponders (PIT) at a resistance board weir installed at a dam removal site (river kilometer (rkm) 56 in 2007, rkm 4 in 2008-2010) and followed migrations with upstream PIT antennas in 2008-2010. This gear proved very effective in low to moderate flows as thousands of fish were tagged and monitored, but less effective in high flows. Fish migrations were strongly influenced by river flow, with most movement occurring during freshets, high flow events following rain. Connectivity between reaches increased following dam removals, with use of restored habitat varying by species. For example, 24-31% of anadromous American shad *Alosa sapidissima*, 45-49% of resident gizzard shad *Dorosoma cepedianum*, and 4-11% of introduced flathead catfish *Pylodictis olivaris* passed the rkm 56 dam removal site. For these species, 17-28% did not pass the partially removed dam (rkm 8) while 20-39% remained downstream for more than a day before migrating upstream. This suggests the notched dam may impede or delay migrations, potentially limiting access to habitat while increasing energy expenditure and predation vulnerability. I further evaluated American shad, an ecologically and economically important species that has experienced prolonged population declines. During freshets, American shad weir captures increased,
migrations were more extensive and faster, and diel activity shifted to daytime hours. Considerable weight loss occurred and displayed a positive relationship with thermal days (cumulative temperature during residence). Proportional weight loss was primarily less than 30% for males and 50% for females, indicating potential thresholds for survival to emigration. Spawning survival was low as estimates ranged from 0.07 to 0.17; no factors (e.g., sex, size, migrations) influencing survival were documented. Estimated American shad abundance increased from 2007 through 2009, but decreased in 2010. Flathead catfish were most common in May and in lower river reaches, increased annually from 2008 to 2010, and were documented consuming American shad. I estimated flathead catfish consumed 237 to 1,278 American shad (7-36% of estimated run size) in 2010. Lastly, I developed a linear spatial capture-recapture Cormack-Jolly-Seber model capable of analyzing the plethora of data collected at continuous monitoring stations (e.g., PIT antennas, telemetry receivers) and applicable to a variety of aquatic and terrestrial systems. I analyzed the model using a Bayesian framework and estimated survival and activity centers (i.e., mean location) and measures of uncertainty (i.e., credible intervals) in each time period. I demonstrated the model with 2010 American shad data. Estimated weekly survival (0.80) was consistent with a non-spatial Cormack-Jolly-Seber model. Activity centers and a movement parameter showed individuals migrated greater distances during higher flow conditions. This study provides strong support for efforts to restore currently inaccessible habitat through complete removal of derelict dams, substantially increases information on spawning American shad that could aid restoration efforts, and provides a model applicable for any linear array (e.g., rivers, shorelines, corridors), opening new opportunities to study demographic parameters, movement or migration patterns, and habitat use.
Factors Influencing Distribution and Survival of Migratory Fishes Following Multiple Low-Head Dam Removals on a North Carolina River

by

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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Fisheries, Wildlife, and Conservation Biology

Raleigh, North Carolina

2012

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DEDICATION

I dedicate this dissertation to Meredith Raabe, for her endless support (including field work), always brightening my day, and being an all-around incredible wife, mother, and person.
BIOGRAPHY

I was born and wonderfully raised by Kent and Christine Raabe outside of Milwaukee, Wisconsin along with my siblings Audra and Joel. As a child, I loved playing sports and following the Milwaukee Brewers, Green Bay Packers, and Marquette University basketball, but also asked for an Audubon Field Guide at each birthday and Christmas. We were very fortunate to travel the world, and my favorite trips involved nature, wildlife, and fishing. I eagerly anticipated each and every opportunity to explore the outdoors, especially water, whether the neighborhood pond or drainage ditch, a Wyoming or Alaskan stream, or the great-wide open ocean. I spent considerable time catching fish, frogs, and turtles at my Nitschke grandparents’ ponds at “The Land” and my Raabe grandparents’ “The Lake.” I soon realized that by better understanding where fish lived, what they ate and when, the more fish I could catch. Therefore, I started reading every fisheries book and magazine I could get my hands on to learn about all things aquatic.

Throughout my years at Wisconsin Lutheran High School, I never really considered a career in fisheries, but then again, I never considered a career period instead focusing on playing sports and attending as many music concerts as possible. However, my aquatic biology class at Augustana College with Dr. Kevin Geedey changed my outlook for good. Never before had I so looked forward to the next class period and was thrilled to learn that I could develop a career of being outside and working with fish. Upon my 2003 graduation I worked as a water resources specialist and fisheries technician with the Wisconsin Department of Natural Resources. I loved sampling fish, but aspired to become a biologist so I could plan and write studies and management plans. That pursuit led me to the
University of Wisconsin – Stevens Point in 2004, where as a Master’s student under the guidance of Dr. Michael Bozek I developed an understanding of the need for innovative research and fisheries management but also a new, rather peculiar interest in statistics and modeling. Armed with these expanded understandings and interests, my steadfast love of fish, and a long-standing desire to teach I pushed forward and started a PhD program in 2007 at North Carolina State University with Dr. Joseph Hightower. This proved to be a wise career and life decision, as I have thoroughly enjoyed my research project on dam removals and migratory fishes, taught multiple classes, learned from a variety of courses, developed special friendships and professional relationships, met my wife Meredith, and we recently had our first child, Rylee Mae. I feel incredibly blessed and am excited for the future.
ACKNOWLEDGMENTS

This project and associated travel was possible due to multiple funding sources. I thank the United States Fish and Wildlife Service (USFWS) for funding the bulk of the study. In particular, I’m very appreciative to Mike Wicker with the USFWS for securing funding and for his insight and assistance. I thank Wilson Laney (USFWS) for funding additional passive integrated transponders and antennas, and always keeping me in the loop. I am thankful to Restorations Systems, LLC, for funding all fish weir materials and for their continued interest in the study. I received travel awards from the American Fisheries Society, North Carolina State University, and the Raleigh Saltwater Sportfishing Club.

I feel fortunate to have a committee that helped me develop as a researcher and teacher as all members were engaged, helpful, and excellent in the classroom. Dr. Joseph Hightower epitomizes everything one could ask for in a PhD advisor: knowledgeable, patient, resourceful, prompt, and motivating. I cannot thank him enough for this opportunity, and am continuously amazed at his professionalism, productivity, enthusiasm, and willingness to explore new research and teaching ventures. Dr. Derek Aday provided the opportunity for me to teach two very worthwhile courses (Limnology; Fish Biology, Ecology, and Management) and has been an excellent teaching and life mentor. Dr. Kenneth Pollock opened my eyes to the world of mark-recapture methods. A renowned expert in this field, he is always humble, able to explain things at basic level, and a fun person to know. One of my first NCSU classes was Dr. George Hess’ Modeling Biological Systems, which was extremely challenging but one of the best courses I have ever taken. I hope to recreate his classroom settings where students are engaged in real-world, purposeful projects.
Many other people have made my project and experiences at NCSU possible. Dr. Beth Gardner was absolutely instrumental with my linear spatial capture-recapture model in Chapter 4. Dr. Thomas Kwak has been insightful, encouraging, and very helpful with networking. I really enjoyed working closely with Dr. James Rice while co-president of the Student Fisheries Society. I cannot count the number of times Wendy Moore helped me with budgets and logistical issues, even when it was last minute and she had to be creative. Susan Marschalk and Meredith Henry also provided great assistance with administrative issues. I have to thank Julianne Harris, now Dr. Harris, for allowing me to follow in just about all of her footsteps along the way and for her help in the field, classes, and office.

My field research and the whole process were only possible due to tremendous assistance. I am thankful to Cherry Hospital and the City of Goldsboro water treatment plant for providing prime access to the Little River. Steve Moore with NCSU helped secure housing at Cherry Hospital, a perfect location adjacent to the fish weir. Field technicians Dana Sackett, Will Smith, John Bain, and Donald Danesi all offered new ideas, worked endlessly, and made each year enjoyable. I am extremely grateful to the many, many people that helped with brute labor in transporting, installing, and removing the fish weir. Michael Fisk, Patrick Cooney, Jared Flowers, Mike Waine, Kevin Magowan, Jacob Hughes, Joe Smith, Ben Wallace, and Dan Weaver helped tremendously, including some bringing their field technicians with them. Taylor Jackson canoed the river with me to help finish habitat sampling. Bob Barwick and Justin Homan with the North Carolina Wildlife Resources Commission also helped with the weir and scanned Neuse River American shad for PIT tags. Krishna Pacifici provided substantial statistical and computing assistance, and Matthew
Krachey also helped in this category. Bryn Tracey with the North Carolina Division of Water Quality was so helpful with courses I taught, the Student Fisheries Society, and his enthusiasm is contagious. Dr. Wayne Starnes and Gabriela Hogue at the North Carolina Museum of Natural Sciences provided access to preserved specimens and species lists. I enjoyed working with and getting to know fellow fisheries graduate students, including Lindsay Campbell, Jessica Baumann, Marybeth Brey, Steve Midway, Tim Ellis, Gus Engman, and Tomas Ivasauskas and many other NCSU and agency people along the way.

Finally, I thank God, my entire family, and my long-time friends for providing support and encouragement throughout my life and during this degree. I still cherish all the times with Grandpa Nitschke fishing, hunting, and working on projects at “The Land” along with his sense of humor and laid back attitude. My siblings, Audra and Joel, have expressed great interest in my research, are true friends, and have awesome spouses. All of my in-laws have been so supportive and helped make Raleigh feel like home. I would never be where I am today if not for my parents, Kent and Christine, who have provided unconditional love, encouragement, support and means to follow my dreams, and are my main role models. I confirmed that my wife Meredith was “the one” when she eagerly threw on waders and sampled fish late into the night. She helped me build portions of the fish weir, was my weekend field technician, endured my time away during field seasons and late office nights, and has helped make this all possible and enjoyable. Smiles from our daughter, Rylee Mae, turned tough days into great ones and she provided extra incentive to finish up.
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CHAPTER 1

Introduction

Dams provide human benefits including water supply, energy production, flood control, and recreation, but they also influence entire riverine communities by altering connectivity, habitat, flow regimes, and fragmenting populations (Poff and Hart 2002; Doyle et al. 2003; Freeman et al. 2003). Even small dams (e.g., <5 m) have resulted in fish extirpations, decreased abundance, reduced movement, and increases in non-native species (Porto et al. 1999; Tiemann et al. 2003; Cumming 2004). Migratory fishes are especially susceptible to the presence of dams as they use different reaches or habitats to complete life cycles (Freeman et al. 2003). In the few studies to date, native fish species respond positively to dam removals including recolonization, increased biomass, and depositing eggs in restored habitat (Kanehl et al. 1997; Catalano et al. 2007; Burdick and Hightower 2006). However, additional studies are necessary to further evaluate differences between systems, species, and success metrics. Questions also remain about the benefits of increased access to restored habitat compared to energetic costs of making longer migrations into these habitats (Leggett et al. 2004).

Evaluating the response of anadromous and resident migratory fishes to dam removals and environmental conditions could aid restoration efforts and flow regime management. Migrations are influenced by water temperature, flow, and other factors (Jonsson 1991), but further evaluations in both natural and regulated rivers are warranted. Anadromous fishes are often focal species in dam removal efforts due to their extensive migrations into rivers to spawn, ecological importance in both freshwater and marine
systems, popularity in recreational fishing, and importance to commercial fisheries. Despite extensive management, restoration efforts, and research, many anadromous species, including American shad *Alosa sapidissima*, have experienced drastic, prolonged population declines (Hightower et al. 1996; Limburg and Waldman 2009).

Many resident or potamodromous fishes, species that reside entirely in freshwater but make distinct migrations during their life cycle, have received less management and research efforts on their migrations and response to dam removals (Freeman et al. 2003; Cooke et al. 2005). Gizzard shad *Dorosoma cepedianum* are an important forage species in lakes, reservoirs, estuaries, and potentially rivers, but relatively little is known about their lotic migrations. Only recently have studies focused on redhorses *Moxostoma spp*., with minimal studies on their migrations. Redhorses often have high biomass and may influence ecosystems through grazing, nutrient cycling, serving as terrestrial prey, and transporting mussel glochidia (Cooke et al. 2005). Large bodied catfishes (Ictaluridae) have been introduced into southeastern rivers, with a few studies examining their predation on native fishes (Pine et al. 2005, Baumann and Kwak 2011) but limited information on migrations and consumption potential exists (Pine et al. 2007).

The study of dam removals, and many migratory fishes, has been limited in part due to difficulties in sampling rivers and mobile species (Lucas and Baras 2000). Rivers are highly dynamic, presenting sampling and safety issues. Comparison between years and rivers, including using one river as a control, can be problematic as hydrology, habitat, and species composition commonly differ both spatially and temporally. Migratory fishes are challenging to capture, especially in downstream reaches, given their capability to rapidly
move long distances and their propensity to be in a specific location for a relatively short timeframe (e.g., spawning period). Once captured and tagged, telemetry provides information on migrations and habitat use, but battery life can constrain study durations and transponder expenses often limit both the number of fish and species that can be studied (Lucas and Baras 2000).

Given these challenges, I used new methods to capture, monitor, and analyze movements and survival of migratory fishes. I used a resistance board weir, a survey tool increasingly utilized in Alaska and on the Pacific coast (Tobin 1994; Stewart 2002), to enumerate and tag fish while monitoring migrations. My study is the first to use passive integrated transponder (PIT) tags and antennas in a large North Carolina river, allowing me to tag thousands of individuals from multiple species with minimal handling, and to obtain records of tagged fish migrating upstream and downstream at antenna sites. Based on terrestrial two-dimensional models (e.g., Gardner et al. 2010), I developed a linear spatial capture-recapture model capable of statistically examining movement and survival from abundant weir and antenna data.

My goal for this dissertation was to evaluate the use of restored habitat by a riverine fish community following multiple dam removals on the Little River, North Carolina, with closer examination of factors influencing migratory fish migrations and survival. In Chapter 2, I describe my use of a fish weir to examine the entire fish community at two dam removal sites and tag multiple migratory species. I used PIT antenna data to determine habitat connectivity, use of restored upstream habitat, passage at a partially removed dam, and to increase understanding of migrations and their relationships with environmental factors. In
Chapter 3, I focus on American shad, examining their demographics, migrations, weight loss, swimming speeds, diel activity, abundance, and providing the first known estimates of spawning season survival and consumption by flathead catfish. In Chapter 4, I describe a linear spatial capture-recapture model I developed that is capable of estimating both demographic and spatial parameters from abundant data collected at continuous monitoring stations (e.g., PIT antennas, telemetry receivers). I used the model to analyze 2010 American shad survival and movement in the Little River, but the model is applicable to any linear array (e.g., rivers, lake shorelines, coastal routes corridors) and opens new opportunities to study survival, migration and movement patterns, and habitat use. Finally, Chapter 5 provides my conclusions and suggestions for future research.
REFERENCES


CHAPTER 2

Assessing Benefits to Migratory Fishes of Habitat Restored by Dam Removal

ABSTRACT

Migratory fish species are assumed to benefit from dam removals that restore connectivity and access to upstream habitat, but few studies have evaluated this assumption. Therefore, I assessed behavior of migratory fishes in the springs of 2007 through 2010 on the Little River, North Carolina, a tributary to the Neuse River with one partial and three complete dam removals. I tagged migratory fishes with passive integrated transponders (PIT) at a resistance board weir located at a dam removal site (river kilometer (rkm) 56 in 2007, rkm 4 in 2008-2010) and followed their migrations with upstream PIT antennas in 2008-2010. Each gear proved very effective in low to moderate flows as thousands of fish were tagged and monitored, but less effective in high flows. Fish migrations were strongly influenced by river flow, with most movement occurring during freshets. Use of upstream restored habitat varied by species. For example, 24-31% of anadromous American shad *Alosa sapidissima*, 45-49% of resident gizzard shad *Dorosoma cepedianum*, and 4-11% of introduced flathead catfish *Pylodictis olivaris* passed the rkm 56 dam removal site. For these species, 17-28% did not pass the partially removed dam (rkm 8) while 20-39% remained downstream for more than a day before migrating upstream. Gizzard shad required the deepest water to pass the notched structure, followed by American shad then flathead catfish. Delayed American shad may experience increased energy expenditures and predation vulnerability; I documented predation by flathead catfish. The results provide strong support for efforts to restore currently inaccessible habitat through complete removal of derelict dams.
INTRODUCTION

Despite inherent complexities, dam removal is becoming an increasingly common strategy aimed at restoring river function and reversing negative impacts on native riverine fauna. Though restoring functional metrics such as physical habitat, water quality, flow, thermal regime, sediment transport, and connectivity is a primary impetus for dam removal (Ligon et al. 1995; Poff and Hart 2002; Tiemann et al. 2004), safety and economics also play important roles. Dam removal is typically less expensive than maintaining or repairing aging dam structures that have reached their functional lifespan and no longer serve their intended purposes (Kanehl et al. 1997; Doyle et al. 2003; Stanley and Doyle 2003). Nevertheless, the dam removal process is usually contentious due to differences in stakeholder perceptions and user group interests (Born et al. 1998; Lejon et al. 2009) and because few scientific studies have evaluated the ecological response (Doyle et al. 2003; Stanley and Doyle 2003; Burroughs et al. 2010). Studies are necessary to inform all stakeholders and to address uncertainty associated with the likelihood of dam removal meeting project objectives (Doyle et al. 2003).

Dams affect entire fish communities, and the few studies conducted to date indicate native fish communities respond positively to dam removals. Large dams (e.g., >15 m height) drastically change connectivity and habitat, with the upstream impoundment transforming from lotic to lentic, while downstream the flow, water quality, and sediment load are altered (Ligon et al. 1995; Pringle et al. 2000; Poff and Hart 2002). Following dam construction, fish communities become fragmented, with both upstream and downstream communities experiencing shifts including extirpations, fewer fluvial specialists, native to
non-native dominance, and thermal preference changes such as warmwater to coolwater (Bain et al. 1988; Winston et al. 1991; Martinez et al. 1994; Quinn and Kwak 2003). Although connectivity and habitat changes associated with small dams (e.g., <5 m) may be less drastic (Poff and Hart 2002), their presence has influenced fish communities both upstream and downstream of dams through extirpations, decreased abundance, reduced movement, and increases in non-native species (Porto et al. 1999; Tiemann et al. 2003; Cumming 2004). Nearly all removals to date have been small dams (Doyle et al. 2003), and results have been promising for native fish populations. For example, within five years of dam removals on two Wisconsin rivers measures of fish biotic integrity improved, species recolonized upstream habitat, and species intolerant to pollution thrived while tolerant species such as non-native common carp *Cyprinus carpio* declined (Kanehl et al. 1997; Catalano et al. 2007). Similarly, Burroughs et al. (2010) documented species recolonization and increased abundance in upstream habitat following removal of a low-head dam in Michigan.

Migratory fishes may benefit considerably from dam removals. For potamodromous species, dams may physically alter or create migratory barriers to important spawning, nursery, foraging or refuge habitat (Pringle et al. 2000; Schmetterling and McEvoy 2000; Freeman et al. 2003). The loss of historic spawning and nursery habitat upstream of dams has been considered one of the main factors in the decline of anadromous fishes (Freeman et al. 2003; Hamilton et al. 2005; Limburg and Walden 2009), including extirpation and imperilment of hundreds of native stocks of Pacific salmon species (Nehlsen et al. 1991). Spawning migrations of tagged American shad *Alosa sapidissima* and striped bass *Morone*
saxatilis were impeded by a low-head dam on the Neuse River, North Carolina (Beasley and Hightower 2000) until removal that resulted in increased use of upstream habitat for spawning (Burdick and Hightower 2006). Weaver et al. (2003) documented a variety of potamodromous and diadromous species, including American shad, passing through a vertical slot fishway on the Upper James River, Virginia, following removals and notches of nearby, downstream dams.

Although these studies provide insights into the response of dam removals by fish populations, many dam removals go unstudied, due in part to difficulties in study design and sampling rivers and migratory fishes. Collection of pre- and post-dam removal data allows assessments of changes following removals, but requires long-term and expensive efforts. A study design that includes concurrent study on one or multiple similar rivers (e.g., geography, hydrology, species composition) may allow researchers to determine responses to dam removals compared to temporal or environmental changes, but requires increased effort and expenses and adequate rivers may not be available. Sampling effectively and safely is a function of river size and dynamic conditions such as flow, gage height and water clarity (Casselman et al. 1990; Lucas and Baras 2000). Sampling can be especially challenging when studying migratory fishes given their capability to rapidly move long distances and their propensity to be in a specific location for a relatively short timeframe (e.g., spawning period; Lucas and Baras 2000; Fullerton et al. 2010). Every sampling gear has trade-offs. Electrofishing and netting have selection biases (e.g., fish size and behavior), and catch rates may vary due to river conditions rather than actual abundance, but they also capture broadly enough to allow effective examination of widespread changes in species composition and
relative abundance (Casselman et al. 1990; Lucas and Baras 2000; Porto et al. 1999). Non-intrusive hydroacoustic gear allows enumeration of fish abundance but typically cannot distinguish species, requires technical expertise, and is expensive (Banneheka et al. 1995; Burwen and Fleischman 1998; Lucas and Baras 2000). Radio and sonic telemetry provides information on migrations and habitat use, but capture, handling, and tagging can affect migrations, battery life can constrain the duration of the study, and transponder expenses often limit the number of fish and species that can be studied (Beasley and Hightower 2000; Lucas and Baras 2000; Frank et al. 2009).

Given these limitations and challenges, new methods are needed to evaluate the response of fishes to dam removals and to increase knowledge of the ecology of migratory fish species. My goal was to evaluate a riverine fish community, in particular migratory species, following dam removals on the Little River, North Carolina, using recent advances in fisheries gear. I used a resistance board weir, a gear increasingly deployed in Alaska and on the Pacific coast (Tobin 1994; Stewart 2002), to enumerate and tag fish while monitoring migrations. Passive integrated transponder (PIT) technology provides accurate and inexpensive lifelong fish identification (Prentice et al. 1990), allowing me to tag thousands of individuals from multiple species with minimal intrusion, and to obtain records of tagged fish migrating through antennas (Castro-Santos et al. 1996; Hewitt et al. 2010). My specific objectives were to determine connectivity and restored habitat use, assess fish passage at a partially removed dam, evaluate migratory responses to physical variables, and examine the effectiveness of the fish weir and PIT technology.
STUDY SITE

The Little River has an extensive history with low head, run-of-river dams, including three complete dam removals since 1998 (Figure 2.1). It is a fourth order tributary to the Neuse River, with the confluence near Goldsboro, North Carolina, approximately 212 river kilometers (rkm) from Pamlico Sound. Buffalo Creek is the primary tributary to the Little River. Cherry Hospital Dam, removed to grade in May of 1998, was located 3.7 rkm from the Neuse River confluence. The dam spanned 41 m long by 2.1 m high and was built in the late 1940s to impound water for the hospital, which has since switched to a municipal water source (NCDENR 1998). Rains Mill Dam, located at rkm 37.7, was removed to grade in December of 1999. The dam measured 76 m long by 3.7 m high, impounded 11 ha, and was constructed in 1928 to power a grist mill that was no longer in use at the time of removal (Wicker 2000). Marine Corps Air Station combat engineers removed the dam during a training exercise (Wicker 2000). Lowell Mill Dam, located at rkm 56.2, was removed to grade in December of 2005 by Restoration Systems, LLC. The dam was constructed in 1902 to power a grist mill that was no longer in use at the time of removal, impounded 17.5 ha over eight river kilometers, and measured 76 m long by 4 m high (Riggsbee et al. 2007).

Additional dams remain on the Little River (Figure 2.1). A partially removed, or “notched”, dam at the City of Goldsboro water treatment plant remains relatively close to the mouth of the river (rkm 7.9; Figure A.1). The Little River served as the primary water source for the treatment plant from when it opened in 1914 until 1974 when the Neuse River became the primary water source; records of dam construction and notching are absent. The structure spans 32 m, with a relatively level spillway along the central portion notched (approximately
0.9 m in height) that extends approximately 11.4 m (Wildman et al. 2011). Concrete rubble leads up to the spillway at a slope of approximately 0.15 m/m, while the impoundment may extend up to 2.9 rkm during low flow conditions (Wildman et al. 2011). Atkinson Mill Dam is the furthest intact downstream dam, located at rkm 82.3, where a grist mill is still active but no longer powered by water. An earthen dam was first constructed in 1757 (Hairr 2007), but the current concrete structure, measuring 30 m long by 4 m in height, was constructed in 1930 and impounds up to 97 ha (NCDENR 2010).

The affect of these dams on the Little River fish community is unclear given that no pre-dam or pre-removal studies exist. Fish species composition is typical of a coastal North Carolina stream (Menhenick 1991), including anadromous American and hickory shad *Alosa mediocris* along with additional migratory, resident species including gizzard shad *Dorosoma cepedianum*, catfishes (*Ictalurus* spp. and flathead catfish *Pylodictis olivaris*) and suckers (*Moxostoma* spp.). Based on a literature review and interviews, Collier and Odom (1989) concluded that Cherry Hospital (river kilometer (rkm) 3.7) and the City of Goldsboro water treatment plant (rkm 7.9) dams were obstructions to anadromous fish migrations, but were “passable at some flows,” while Rains Mill Dam (rkm 37.7) was impassable.

**METHODS**

*Fish Sampling and Tagging*

The fish weir was installed each spring (March-May) to monitor migrations and capture fish for tagging. The weir was located at the former Lowell Mill Dam site in 2007, while from 2008 to 2010 it was installed at the former Cherry Hospital Dam site (Figure 2.1).
I installed the weir further downstream in 2008 to encounter migratory fishes as they entered and left the river. This location also allowed me to tag fish and monitor their migrations in the Little River with an array of upstream PIT antennas.

I constructed the resistance board weir according to Stewart (2002), with minor modifications to accommodate the conditions and targeted fish species in the Little River (Figure A.2). All portions of the weir and live cages were spaced a maximum of 2.5 cm apart to allow water but not the primary target species (i.e., American shad) to pass through the weir. A steel I-beam with aircraft cable held in place by eye bolts was installed along the river bottom to provide a level, sturdy connection for the resistance board weir panels. A downstream and upstream cage was installed on the opposite ends of the resistance board panels in 2007; only one fish was caught in the downstream cage. Therefore, to improve catch rates of downstream migrating fish, in the middle of the 2007 sampling season I attached a floating net to the downstream end of a panel that was partially sunken by sandbags. Beginning in 2008, I constructed a modified panel with an attached floating cage on the downstream end (Figure A.3). The wider panel (1.3 m) did not have a resistance board and was concave to create a deeper channel into the downstream cage (0.9 m wide, 1.6 m long, 0.6 m deep). The resistance board weir was installed in the area of highest flow, with a total of 13 panels connected to span 12.4 m of the river in 2007 and 2008 and 16 panels in 2009 and 2010 that spanned 15.2 m of the river. From 2008 to 2010 a rectangular, metal-framed upstream cage with vertical conduit pickets was installed adjacent to the west side of the resistance board weir, and picket weirs completed the weir on both sides of the channel. The inside cage dimensions measured 1.5 m wide by 3.0 m long by 3.0 m deep. To
guide fish into the upstream cage, a passage chute (1.5 m wide, 1.0 m long, 3.0 m deep) was attached to the downstream portion of the cage in 2009 and 2010. In all, the weir fully spanned the river channel, measuring around 41 m at both weir sites.

I checked weir live cages each morning, evening, and throughout the day and early night during periods of increased captures. Captured fish were removed with a dipnet, identified to species, examined for sex, measured for total length (mm), and when possible weighed (g). In 2007, individually numbered Hallprint 12/13 mm fine T-bar anchor tags were placed near the base of the dorsal fin of American shad and notchlip redhorse Moxostoma collapsum. I tagged all healthy immigrating and emigrating American shad in 2008 and 2009 with a Texas Instruments PIT transponder (RI-TRP-RE2B). In 2010, I only tagged healthy immigrating individuals because it was the last season of the study. I increased the proportion of other migratory fishes receiving a PIT tag from 2008 to 2010, including tagging all healthy, upstream migrating individuals in 2010. These small tags (3.9 mm x 31.2 mm, 0.8 g) were inserted into the abdominal cavity via a small incision between the pectoral and pelvic fins for most species and along the ventral midline for catfishes; this rapid procedure required no anesthetic. A handheld reader (Allflex Compact Reader RS200) was used to scan all captured fish. Tagged fish were released upstream or downstream, depending on the cage in which they were captured. To characterize sampling effort, I recorded the number of people and duration of stay for each weir visit in 2010.

I used electrofishing to supplement weir captures in 2007 and 2009. A Georator with a portable boom supplied 230V DC for electrofishing from a small jon boat to capture and T-bar tag fish in 2007; all sampling occurred upstream of the fish weir. In 2009, I tagged fish
with PIT tags. I used the Georator unit in middle to lower reaches and conventional electrofishing boats (Smith Root units with pulsed DC current (60 Hz) at 3.0–4.0 amps) in downstream reaches near the fish weir and river mouth.

Passive Integrated Transponder Antennas

I incorporated PIT antennas into the study from 2008 to 2010 to monitor fish migrations without the need for repeated handling of fish (Figure A.4). The Texas Instruments Series 2000 reader, consisting of a control module (RI-CTL-MB2) and a remote antenna radio frequency module (RI-RFM-008), sent a signal at 134.2 kHz that energized and then received a signal from a transponder moving near or through an antenna. The datalogger, developed by Oregon RFID, was wired to the reader and recorded the transponder identification number along with date and time of detection. Data records stored on a memory card were downloaded to a personal digital assistant and then transferred to a personal computer. Two 12 V batteries connected in parallel powered the system. The reader, datalogger, and batteries were housed in a waterproof container. Twinax cable connected the reader to a Texas Instruments tuner box (RI-ACC-008) installed close to the antenna. Changing the jumper configuration on the tuner box capacitor allowed for “tuning” of the attached antenna such that it resonated to provide the greatest read range of transponders. The actual antenna was a continuous loop of eight gauge audio cable spanning the river channel. The upper loop of cable was attached with plastic cable ties to rope or synthetic cable tied to trees or rebar structures on the bank; I tightened the synthetic cable using ratchet straps. The bottom loop of cable was attached with plastic cable ties to rope or
synthetic cable attached to stakes or rebar driven into the substrate. I installed Oregon RFID marker tags in 2009 and 2010 at each antenna to verify continuous antenna operation. These tags, housed in a waterproof container, were located out of the water but within the detection field and were designed to respond to the antenna once an hour. I visited antennas every two to four days to exchange batteries, assure proper tuning, and download data.

Three PIT antennas were installed on the Little River in 2008 (Figure 2.1). An antenna was located 190 m downstream of the notched dam at the Goldsboro water treatment plant (rkm 7.7) and another antenna was installed across the notched dam (rkm 7.9). The final antenna was installed 169 m upstream of the former Lowell Mill Dam and 2007 weir site (rkm 56.4). Upon weir removal near the end of the 2008 field season, the Lowell Mill Dam antenna was relocated to the weir site (rkm 3.7) to monitor final emigrants.

Additional PIT antennas were installed in 2009 and 2010 on the Little River (Figures 2.1, A.4, and A.5). A second antenna was installed 5.4 m upstream of the antenna located downstream of the notched dam (rkm 7.7) to assist in determining directionality of tagged fish; a Texas Instruments multiplex board (RI-MOD-TX8A-00) allowed connection of both antennas to the same reader. Antennas were installed adjacent to a North Carolina Forest Service facility (rkm 13.4) and upstream of the Rains Mill Dam removal site (rkm 37.7) at Rains Crossroads Road (State Road 2320, rkm 45.3). Upstream antennas were located at Shoeheel Road (State Road 2127, rkm 72.0) and Old Dam Road (State Road 2123, rkm 77.0). Upon weir removal, an antenna was transferred to the weir site (rkm 3.7).

Once each season, I measured the detection range at each antenna by slowly moving a PIT tag (length-wise oriented parallel with flow) towards the antenna along a tape measure. I
recorded the distance when tag detection occurred, as indicated by a loud signal emitted by an audio signaling device attached to the reader. Based on antenna width, I recorded detection distances at a minimum of four equally spaced locations. At each location, I measured upstream and downstream distances at the top cable, bottom cable, and in the middle along with above and below the top and bottom cables.

Antennas were not 100% efficient at detecting tagged fish, so I estimated detection rates for each antenna. Seasonal detection rates were calculated as:

\[
\text{number of detections} / \text{total number of possible detections (detections + missed detections)}
\]

Within a migratory sequence, I used only the first detection at an antenna in the estimation; repetitive detections at the same antenna were excluded. Missed detections were any antenna gaps in the migratory sequence. For example, if a fish was detected at antenna one and later at antenna three, a missed detection occurred at antenna two. This calculation includes periods when antennas were not functioning properly (e.g., out of tune), as it was unknown if a missed detection occurred during a fully or less than fully functioning period. Detection rates could not be calculated at the uppermost antenna (Old Dam Road, rkm 77.0).

**Physical Variables**

Onset HOBO-TEMP loggers recorded water temperature (°C) at 1.5-h intervals during the sampling period at the weir sites (Figure 2.1). Water gage height data were obtained from the United States Geological Survey (USGS) monitoring station (0208863200) at Highway 581, immediately downstream of the 2008-2010 weir site (rkm 3.7). A second USGS monitoring station, located upstream (rkm 45) near Princeton (02088500), provided
water discharge and gage height data. I also recorded water depth at the notched dam at a measuring device installed at the shallowest point of the spillway. To standardize to maximum spillway depth, I recorded water depth along the spillway on four occasions, calculated the mean difference between the maximum depth and measurement point depth, and added it (217.5 mm, SE = 17.5 mm) to the daily measurement. I regressed 2010 depths (mm) against the Goldsboro gage height (m) from the same time to estimate hourly maximum notched dam water depth (mm) from 2007 through 2010 (n=35, R^2=0.98):

\[
\text{estimated depth} = -696.14 + 764.45 \times (\text{gage depth}) - 73.64 \times (\text{gage depth})^2
\]

I conducted this analysis, and all other statistical analyses, in program JMP, version 9.0.0 (SAS Institute Inc. 2010)

**Habitat Characterization**

I conducted a habitat survey from the mouth of the Little River to the base of Atkinson Mill Dam. I divided the river into eight reaches according to antenna and weir locations (e.g., reach one: mouth to weir, reach two: weir to notched dam antennas, etc.). Within each reach, I recorded habitat at a minimum of 25 points based on randomly selected distances from the start of the reach. For reaches over five rkm long, I added a minimum of 25 random points for every five rkm (e.g., reach of 15 rkm = minimum of 75 sample points). I marked each habitat point with a Garmin GPSmap 76Cx handheld unit.

At each random sample point I walked or boated the entire wetted width as a transect perpendicular to the flow. When recording data, I considered the entire area within 1.0 m upstream and downstream of the transect. At each sample point, I recorded the habitat type,
dominant and subdominant substrate present, extent of substrate embeddedness, and maximum water depth (mm). Habitat type was categorized as 1. riffle (shallow, turbulent surface, swift velocities), 2. run (relatively shallow but deeper than riffles, smooth surface, swift velocities), 3. pool (relatively deep, smooth surface, slow velocities). I recorded the dominant and subdominant substrates present according to a modified Wentworth (1922) scale: 1. silt/clay <0.062 mm, 2. sand 0.062-2.0 mm, 3. fine gravel 2.1-16.0 mm, 4. coarse gravel 16.1-64.0 mm, 5. cobble-rubble 64.1-256.0 mm, 6. small boulder 256.1-508.0, 7. large boulder 508.1-1024 mm, 8. bedrock >1024 mm. When determining the dominant and subdominant substrates, in the case of ties (e.g., 50% coarse gravel in thalweg, 50% sand in deposition bar) I gave preference to substrate in the thalweg. I also recorded the embeddedness, or degree that sand and silt/clay covered coarser fine gravel, coarse gravel, and cobble-rubble substrates as: 0. two or more clean layers, 1. one clean layer, 2. 50% embedded, 3. 75% embedded, 4. primarily embedded. An embeddedness score of one was assigned to small boulders and larger, and four for sand and silt/clay. At most points, substrate composition and embeddedness were visually estimated, but in turbid or deep areas I probed the substrate with my hands, feet, canoe paddle, or measuring stick.

In addition to collecting data at random points, I qualitatively characterized habitat to develop a continuous record in the Little River from the mouth to Atkinson Mill Dam. While moving downstream in a canoe, I recorded with a Garmin GPSmap 76Cx handheld unit noticeable shifts in habitat type (riffle, run, pool) and dominant substrate. In turbid and deep water, I probed the substrates with a canoe paddle.
I created a continuous habitat map using both random sample and transition points. I digitized the map in ArcGIS 10.0 (ESRI 2010), first outlining the river banks by tracing over an aerial photograph layer. I imported all GPS points with their associated characteristics (e.g., substrate, habitat type). I divided the river into polygons by drawing perpendicular lines (bank to bank) immediately upstream of each GPS point. I joined GPS points and characteristics to each polygon, calculated polygon areas, and exported the data.

*Connectivity and Restored Habitat Use*

I determined habitat connectivity as the total distance traveled by PIT-tagged individuals and the number of times they passed the four different dam sites (previously potential impediments). I calculated the total distance traveled (rkm) as the sum of the distance between locations for all upstream and downstream migrations. An upstream or downstream migration occurred when a fish was detected at a new location; repetitive, sequential detections at one antenna were excluded. An individual could only pass a dam site once within a migratory sequence (e.g., four total passes: upstream at 1, upstream at 2, downstream at 2, downstream 1). I included missed detections within a migratory sequence. Weir captures were considered passage of the former Cherry Hospital Dam; upstream passage of the notched dam was determined with the Forest Service antenna whereas subsequent downstream passage was determined with the antenna immediately downstream of the notched dam. The upstream Rains Crossroads antenna was a proxy for passage of the former Rains Mill Dam while passage of the former Lowell Mill Dam was determined with
the antenna immediately upstream. To ensure fish were healthy and retained tags, I only used fish detected at the Forest Service antenna or upstream in connectivity tallies.

I evaluated restored habitat use in the Little River as the distribution of PIT-tagged fish that migrated through or into different reaches, and the density of tagged individuals in their terminal reach. To account for tagging stresses (e.g., fallback), mortalities, or tag loss, I only used fish detected at one or more antennas (sum = total number of individuals). For each reach (same divisions as habitat survey), if a fish was detected at the reach antenna or an upstream antenna (e.g., missed detection) it was considered to have used that reach (sum = total individuals in reach). I calculated the cumulative seasonal distribution as the number of individuals in a reach divided by the total number of individuals. Because reaches varied in size and the distribution included fish that may have migrated rapidly through a reach, I also computed the density of individuals in their terminal reach. I assigned each tagged individual to a terminal reach based on its furthest upstream detection (maximum rkm) and divided the number of individuals in the reach by the reach area (ha).

*Notched Dam Passage and Delay*

I determined successful passage at the notched dam using antennas immediately downstream, across, and upstream of the structure. I used the upstream Forest Service antenna because the notched dam antenna did not function over the entire study periods. Perilous flow conditions resulted in delayed notched dam antenna installation in each field season while high flows (2008, 2010) and vandalism (2009) severely damaged the antenna. In addition, successful passage of certain tagged fish was ambiguous as they were detected
downstream, at the notched dam, and then again downstream over short time periods. I calculated successful passage of the notched dam as, 1. number of fish detected at the notched dam antenna and 2. number of fish detected at the Forest Service antenna, with both divided by the number of fish detected at the antenna downstream of the notched dam.

During periods when the notched dam antenna functioned properly, I examined successful passage relative to the estimated maximum spillway depth. Fish in these analyses were detected at the notched dam antenna and subsequently at an upstream antenna. I used the last notched dam detection prior to detection at an upstream antenna and matched it to the estimated hourly maximum water depth. Due to relatively low sample sizes, I pooled data from 2009 and 2010 data by species. To evaluate the availability of passage conditions, I used the minimum and median water depths for successful passage and determined the proportion of time these hourly water depths were met or exceeded during the spring (March-May) and annually for 2007 through 2010. I also used simple logistic regression to examine notched dam passage relative to spillway water depth. A value of 1 was assigned to successful passage detections at the notched dam antenna, while a value of 0 was assigned to prior detections (one per hour) at the antenna immediately downstream. I used only the notched dam record if a fish was detected at both antennas within the same hour.

For fish detected successfully passing the notched dam antenna, I computed the potential downstream migratory delay as the time difference between the first detection at the downstream antenna and the last detection at the notched dam antenna. I also calculated the time difference between the last detection at the downstream antenna and the last detection at the notched dam antenna to examine whether fish staged immediately below the notched
dam. To account for the entire spring period, I compared all fish detected at the antenna downstream of the notched dam and at least one upstream antenna (i.e., Forest Service or above) to individuals only detected downstream. I calculated downstream migratory delay as the time difference between the first and last detections (prior to detection at an upstream antenna for individuals that passed) at the antenna downstream of notched dam. For fish detected only once at the downstream antenna (e.g., missed detection, paired antenna absent), I assigned them the mean time difference it took for fish to pass through the paired antennas.

Fish Migrations

I used linear regression to examine potential relationships between fish migrations and environmental conditions. I compared the daily count (square root transformed to meet normality assumptions) of weir captures and antenna detections with different predictor variables including numerical calendar date, and daily gage height, flow, and water temperature (daily mean and coefficient of variation, difference in daily mean from previous day). To focus on whether fish migrated on a particular day, an individual was counted once per day even if captured or detected at multiple times or locations in a day. I used combined weir captures and antenna detections from periods when the weir and antennas were both fully installed: April 15 to May 27 in 2009 and March 10 through June 9 in 2010. These timeframes included days when the weir and certain antennas were not fully functioning. Only fish detected at the Forest Service antenna or upstream were used in analyses. I calculated Akaike’s Information Criterion weights for small sample sizes (AICc) and ΔAICc. All models with a ΔAIC value less than 2.0 were considered to have substantial empirical
support, models with a $\Delta$AIC in the 4.0 – 7.0 range have some empirical support, whereas models with a $\Delta$AIC greater than 10.0 have essentially no empirical support (Burnham and Anderson 2002).

**RESULTS**

*Fish Sampling, Tagging, and Gear Effectiveness*

Over the springs of 2007 through 2010, a total of 7,211 fish captures occurred at the Little River fish weir spanning 6,829 individuals over 28 species (Table 2.1). I PIT-tagged 3,367 individuals from 10 different species at the weir in 2008 through 2010 (Table 2.2).

In 2007, electrofishing upstream of the weir site captured 23 American shad (22 T-bar tagged), 42 notchlip redhorse (34 T-bar tagged), and 37 gizzard shad. American shad were more common in the upstream reach, while notchlip redhorse were more common in the downstream reach and the downstream portion of the upstream reach (Figure 2.2). During seven electrofishing events between the mouth (0 rkm) and rkm 38 in 2009 (April 1-10), I PIT-tagged 16 American shad, 14 notchlip redhorse, six hickory shad, four gizzard shad, and one shorthead redhorse *Moxostoma macrolepidotum*. I also PIT-tagged three American shad in the Neuse River by electrofishing immediately downstream of the Little River.

The fish weir captured a large number and diversity of fish, but did not function properly during higher flows (Figure 2.3). Low to moderate flows required to install the weir commonly delayed installation from the intended (March 1) starting date in each year. The weir functioned properly in low to moderate flows by completely covering the entire river channel and water depth. I considered non-functioning periods to be days when the full river
channel and water depth were not covered by the weir. These periods occurred in moderate and high flow conditions, when fish could potentially pass over the weir due to partially submerged or fully submerged resistance board panels, damaged portions of the weir, or flooding that allowed fish to swim over and around the weir. The most damage occurred in 2009 when the entire resistance board weir and I-beams washed downstream to the HWY 581 bridge. The weir functioned the least days in 2009 and most days in 2010.

I observed mortalities and “fallback” (recapture within 24 hours of release) at the fish weir (Table 2.3). American shad accounted for 92% of all mortalities in the upstream cage, with the rate varying between 31% in 2007 to 4% in 2010. Other species suffering minimal (i.e., 1-4/year) mortalities in the upstream cage were gizzard shad, hickory shad, American eel *Anguilla rostrata*, black crappie *Pomoxis nigromaculatus*, and longnose gar *Lepisosteus osseus*. Downstream mortalities were more prevalent, both in the downstream cage and on the resistance board panels, with American shad accounting for the majority (78%), followed by hickory shad (9%), notchlip redhorse (5%), and gizzard shad (4%). I observed very high mortality (90%, 44 of 49) and poor condition of downstream migrating notchlip redhorses in 2007 (Figure A.1); these mortalities were not influenced by capture, handling, or tagging as no individuals were recaptures from the weir or electrofishing. Fish that entered and were removed from the downstream cage had higher survival rates than fish removed from the resistance board panels. However, the ratio of fish entering the downstream cage compared to stranding on the panels varied by year and species. American shad were the most vulnerable species to fallback responses.
The fish weir was labor intensive. In 2007, initial weir construction took approximately six to eight weeks and installation took one week. Weir additions, modifications, and repairs in 2008 through 2010 took approximately two to four weeks in each year while installation time was reduced to one day of material transport and approximately two days of installation with the assistance of three to eight people. I visited the fish weir a mean of four times per day in 2010, with a daily mean of four hours and seven minutes of fish sampling. When combining total human effort, the mean daily sampling time increased to six hours and 51 minutes with a range of 50 minutes to 12 hours and 53 minutes.

The PIT antennas provided substantial data from detected fish (e.g., 34,970 total detections in 2010), but issues arose higher flow conditions (Figure 2.4). Higher flows at times delayed installation of antennas. Antennas functioned properly (e.g., detected marker tags, tagged fish) under low to moderate flow conditions. Antenna efficiency decreased (e.g., missed marker tags, tagged fish) when antennas became out of tune during increasing flows that submerged the top cable, resulting in debris accumulation and drag. Antenna detection fields also did not fully cover the channel and water column during high flow and flood events. Antennas functioned the most days in 2010 and least days in 2008.

Downstream antennas were typically horizontally wider and vertically deeper, while narrower, deeper upstream antennas tended to have higher read ranges (Table 2.5). Test tags were always detected inside of antennas and below the bottom cable. The vertical middle of the antenna had the highest read range. The highest mean (multiple measurements along an antenna) read range extended 1.04 m from the middle of the Old Dam Road antenna.
Antenna read ranges above the top cable ranged from 0.27 to 0.65 m, while low read ranges occurred when the PIT tag moved directly towards the top and bottom cables.

Antenna detection rates varied by species and year, in part due to differences in periods of when fish were tagged and antennas were functioning (Table 2.6). For example, gizzard shad detection rates were relatively low in 2009 when a number of individuals were tagged prior to downstream antenna installations. The notched dam antenna (rkm 7.9) had reasonable detections rates in 2009 but very low detection rates in 2010 as numerous fish were tagged and migrated upstream prior to installation. In contrast, the Rains Crossroads antenna (rkm 45.3) did not function well in 2009 and had low detection rates but functioned better in 2010. Detection rates could not be computed for Old Dam Road (rkm 77.0), but the antenna had high read ranges and detected a comparable number of individuals to the Shoeheel Road antenna (rkm 72.0).

Certain PIT-tagged fish were never recaptured at the weir or detected at an antenna in the same spring sampling season (Table 2.7). This occurred most often for American shad, hickory shad, and gizzard shad and the least often for catfishes. Lower rates in 2008 may be due to the fewer antennas and functioning days. Compared to the fish weir, a higher percentage of fish that were never recaptured or detected was observed for individuals tagged via electrofishing in 2009, with American shad at 87.5% (16), notchlip redhorse at 71.4% (14) and all gizzard shad (6), hickory shad (6) and shorthead redhorses (1). One of three American shad tagged in the Neuse River was detected in the Little River.
Connectivity and Restored Habitat Use

American shad were the most abundant species captured in all four years and at both weir locations (Table 2.1). Three other anadromous species (hickory shad, blueback herring *Alosa aestivalis*, striped bass) were sampled at the downstream but not upstream weir location; the catadromous American eel was sampled at both locations. Potamodromous gizzard shad were the second most abundant species at the upstream location in 2007 and abundant downstream in the other years. A noticeably higher number of potamodromous notchlip redhorse were captured at the upstream location while catfishes and longnose gar were most abundant downstream. Flathead catfish captures increased substantially from 2008 to 2010 at the downstream weir site.

Complete and partial dam removals appeared to increase connectivity among river reaches for migratory fishes (Table 2.8, Figure 2.5). Numerous gizzard shad made multiple, long upstream and downstream migrations throughout the spring period resulting in the highest mean total distance traveled and total times passing a dam site. American shad also moved through multiple reconnected reaches, but many individuals did not initiate or complete emigrations, resulting in the second highest total distance traveled and dam sites passed. Fewer flathead catfish migrated into upstream reaches, resulting in the lowest total distance traveled and fewer dam sites passed.

Migratory fishes use of restored habitat varied by species and was highest in 2010 (Table 2.9). Electrofishing in 2007 captured American shad and gizzard shad just downstream of Atkinson Mill Dam (rkm 82), confirming use of the entire extent of restored habitat. All 2007 weir captured fish migrated past the former Lowell Mill Dam, and if
immigrating from the Neuse River (e.g., American shad), also passed the three downstream dam sites. All 2008 through 2010 weir captured fish migrated past the Cherry Hospital dam removal site. The proportion of 2009 and 2010 tagged individuals migrating into upstream reaches declined in a linear fashion after an initial drop-off at the Goldsboro notched dam, with some species variation. For example, gizzard shad used upstream reaches to the highest extent, followed by American shad, and a few flathead catfish (Figure 2.6). Flathead catfish and channel catfish *Ictalurus punctatus* had similar trends in 2010 including a few individuals migrating past rkm 77, while no blue catfish *Ictalurus furcatus* and only two redhorses were detected upstream of rkm 13.

Densities of tagged fish in their maximum upstream reach provided slightly different restored habitat use patterns (Figure 2.7). All species, and in particular American shad, had higher densities in the downstream reach (rkm 8-13) that included the notched dam. American shad and gizzard shad densities stayed relatively similar between rkm 13 and 56 while flathead catfish densities were slightly higher between rkm 13 and 45. American shad and gizzard shad both had increased densities in the two uppermost reaches (rkm 72-82).

Little River habitat varied by reaches (Table 2.10, Figure 2.8). Lower reaches (rkm 0-13) were dominated by sand, with areas of silt and fine and coarse gravel; the mean substrate embeddedness reflects dominance by fine substrates. Habitat complexity increased in middle and upper reaches (rkm 13-82) with the addition of cobble/rubble and larger substrates with more interstitial spaces (lower substrate embeddedness). The long reach between rkm 13 and 45 contained a high proportion of sandy, pool habitat but also had riffle and run sections with a diversity of coarse substrates (fine gravel and larger). The reach
between rkm 45 and 56 had the highest proportion of coarse substrates. In the uppermost reaches, the reach between rkm 72 and 77 had more boulders while the reach downstream of Atkinson Mill Dam (rkm 77-82) contained the highest proportion of cobble/rubble substrates.

*Notched Dam Passage and Delay*

The notched dam appeared to influence fish migrations to varying degrees (Table 2.9). Upstream passage rates at the partially removed dam for tagged fish detected at one or more antennas were lower in 2009 than 2010 and ranged from 0.38 for blue catfish to 0.83 for gizzard shad, both in 2010. Passage rates using the Forest Service antenna were lower than the notched dam antenna, but likely more reliable estimates as the antenna functioned for longer periods of time and fish clearly passed the entire structure.

Apparent downstream delays prior to passing the notched dam varied by species, years, and individuals. Based on both delay metrics, delays were generally longer in 2009 than 2010 and gizzard shad experienced longer mean delays than American shad or flathead catfish in both years (Tables 2.11, 2.12). During periods when the notched dam antenna functioned, individual delays ranged from less than 10 minutes for an American shad up to 37.5 days for a gizzard shad (Table 2.11). American shad and flathead catfish spent considerable time staging immediately downstream of the notched dam while gizzard shad tended to migrate downstream during delays (Table 2.11). When considering the entire spring periods, the notched dam appeared to delay 20 to 39% of American shad, gizzard shad, and flathead catfish for longer than one day (Table 2.12). Individuals that never passed the notched dam tended to spend longer durations downstream (Table 2.12).
American shad, gizzard shad, and flathead catfish displayed similar patterns when reaching the notched dam, but differences did exist between species and individuals (Figure 2.9). Only American shad individuals reached the notched dam and returned to the fish weir (Figure 2.9a). More commonly, individuals from these species reached the notched dam, remained downstream for a time period, and then were no longer detected or recaptured in the spring (Figure 2.9b). A few individuals were detected migrating upstream at the notched dam and then shortly thereafter at the antenna downstream, apparently unsuccessfully passing the structure or passing but immediately migrating back downstream (Figure 2.9c). The majority of downstream delays occurred when individuals reached the notched dam during decreasing or low water levels, potentially attempting to pass (Figure 2.9d) or remaining downstream (Figure 2.9e) prior to passing during increasing flows and water levels. Individuals that experienced minimal downstream delays typically passed rapidly during increasing or high flow conditions (Figure 2.9e).

Based on the maximum water depth along the notched dam spillway when tagged individuals successfully passed the notched dam, gizzard shad required the deepest water, followed by American shad and then flathead catfish (Table 2.13). The minimum depth that each species passed the structure was typically available in the spring periods but availability of water depths at median passage was noticeably lower. Annually, availability of water depths for both minimum and median passage decreased considerably. Simple logistic regression analyses indicated the relative probability of notched dam passage increased with water depth for all three species, although the relationship was insignificant for flathead catfish (p=0.777; Figure 2.10). American shad (p<0.001) displayed the strongest response to
increasing water levels, with the model predicting a passage rate of 0.70 at a water depth of 900 mm. In comparison, gizzard shad predicted passage (p=0.006) was 0.35 at 900 mm.

*Fish Migrations*

Given the weir location in 2007, weir captures provided information on migratory cues for individuals in upstream reaches (Figure 2.11). Relatively few individuals were captured until an April 16 to 18 freshet when individuals migrated upstream, dominated by gizzard shad (216 individuals), six American shad and the only largemouth bass (four individuals) captured in 2007. American shad did not exhibit an observable pattern in upstream migrations in 2007; on both March 28 and April 1 four notchlip redhorses migrated upstream when mean daily water temperatures were 19.9 and 17.4 °C. A considerable number of individuals migrated downstream from April 26 to May 3 when water temperatures ranged from 21.1 to 22.8 °C. American shad (333 individuals) dominated this downstream migration event along with gizzard shad (24 individuals) and poor condition or dead notchlip redhorses (33 individuals). Very few migrations occurred during the rest of May when flow was low and water temperatures high.

The downstream weir location in 2008 through 2010 provided information on Little River immigration and emigration (Figure 2.12). In each year, migrations were more common for all species during increasing flows, and especially evident in 2010. For example, only 28 fish (23 upstream, five downstream) migrated between May 11 and 17, 2010, when flows ranged from 0.43 to 0.71 m³/s (1.3-1.5 m Goldsboro gage height) compared to 335 fish (277 upstream, 58 downstream) migrating during flows of 5.6 to 18.6
m$^3$/s (1.7-3.0 m Goldsboro gage height) in the following week (May 18 to 24) even with the weir not fully functioning during portions of the higher flow week. Downstream migrations were predominantly American shad that displayed distinct emigration events in 2008 and 2009 during freshets when mean daily water temperatures were always above 20 °C. In 2008, 312 American shad emigrated (31% of American shad emigrants) on April 28 and 29. The American shad emigration period in 2009 was even more profound, as 950 emigrated (55% of American shad emigrants) from May 6 through 8. American shad dominated the emigrant composition in 2010, but no large events occurred, even during freshets in late May. A total of 99 American shad emigrated from May 17 through 30 when mean daily water temperatures ranged from 19.1 to 24.1 °C. Gizzard shad immigrated throughout the 2009 and 2010 sampling seasons; the most discernible immigration event occurred in 2009 (39 individuals, 33% of tagged) during increasing flows on March 15 and 16 prior to the weir washing downstream. Flathead catfish immigration occurred throughout the 2009 and 2010 sampling seasons, but was most prevalent in May of 2009 while 24% (39 individuals) of 2010 immigrants were captured during a May 19 to 20 freshet. The few gizzard shad and flathead catfish weir emigrants in 2009 and 2010 were predominately fallbacks.

Fish migrations at PIT antennas tended to mirror weir captures, with detections more common during increasing flow events at all antennas in each year. For example, pulses of tagged American shad, gizzard shad, and flathead catfish migrated past the Forest Service antenna during a small to moderate freshet in early May 2009 (Figure 2.13). The Forest Service antenna functioned throughout 2010, showing these same species migrating in high numbers during large freshets in late March to early April and increased numbers in small to
moderate freshets in March and late May (Figure 2.14). In contrast, very few fish were
detected migrating in late April through mid-May 2010 during low flow conditions. Water
temperatures did not appear as influential to fish migrations (Figures 2.13, 2.14).

Linear regression showed strong, positive relationships between flow variables and
the number of daily weir captures and antenna detections (Figure 2.15). The total daily
captures and detections of American shad, gizzard shad, and flathead catfish combined
ranged from 0 to 163 individuals (square root transformed= 0-12.8); zeroes occurred in 2010
on low flow days (April 24, May 13). Princeton gage height (m; AICc=519.6, R²= 0.622)
and flow (m³/s; AICc=528.8, R²=0.595) with quadratic terms were the best single predictor
models, displaying a positive relationship with daily captures and detections. Similar, but
weaker relationships also existed for Goldsboro gage with a quadratic term (AICc=541.7,
R²=0.555). However, limited relationships existed between daily migrations and Goldsboro
gage height daily coefficient of variation (AICc=607.0, R²=0.278), water temperature (°C;
AICc=634.5, R²=0.115) or numerical calendar date (AICc=643.7, R²= 0.052), all with
quadratic terms. To limit collinearity in multiple linear regressions, I restricted flow
conditions to one variable and its quadratic term (e.g., did not include Princeton and
Goldsboro gage heights or Princeton gage height and its coefficient of variation). The top
model (AICc=496.9) explained 70% of the variation (R² = 0.696) in daily migrations:

\[-9.474 – 0.057*(calendar\ \text{date}) + 12.789*(Princeton\ \text{gage}\ \text{height}) – 3.162*(Princeton\ \text{gage}\ \text{height})^2 + 1.272*(temperature) – 0.025*(temperature)^2.\]

When evaluating migrations by individual species in each year, I focused on 2010
because gear functioned throughout the sampling season and trends were comparable to
2009. Princeton gage height (with quadratic term) was the top single predictor model for
gizzard shad and flathead catfish, explaining 77% and 58% of the variation in daily migration
numbers; river condition metrics displayed a positive, but weaker relationship with American
shad (Table 2.14). Water temperature and calendar date displayed negative relationships
with daily American shad migrations but no relationship existed with gizzard shad or
flathead catfish migrations. Models containing Princeton gage height (with quadratic term),
water temperature, and calendar date explained a comparable amount of variation in
migratory counts between the three species, but the reduction in \( \Delta \text{AIC}_c \) and increase in \( R^2 \) for
American shad was more substantial than for the other two species (Table 2.14).

**Flathead Catfish Predation**

I did not formally study flathead catfish diets, but documented four cases of predation
on American shad. In 2009, an American shad PIT tag was removed from the stomach of a
flathead catfish found dead on the fish weir panels (Figure A.7). Two live flathead catfish
captured in the upstream weir cage in 2010 contained American shad PIT tags tagged earlier
in 2010. In the fourth case, I observed an American shad caudal fin protruding from a live
flathead catfish gullet captured in the upstream cage in 2009 (Figure A.7)

**DISCUSSION**

*Connectivity and Restored Habitat Use*

Multiple fish species, especially migratory fishes, used habitat restored by dam
removals on the Little River. At least 28 different species migrated past one dam removal
site (Lowell Mill in 2007, Cherry Hospital in 2008-2010); additional small-bodied fish species (e.g., Cyprinidae) may have passed through spacing in the fish weir. Catalano et al. (2007) determined nine of eleven fish species, including small-bodied species, recolonized habitat never or rarely occupied upstream of dams in the Baraboo River, Wisconsin, following dams removals. In a Michigan river, Burroughs et al. (2010) found 34 species (counting small-bodied species) above a dam removal site, including eight species that were not found prior to removal. While a lack of pre-removal information precludes a thorough evaluation of species distribution shifts in the Little River, at a minimum, anadromous American shad and resident gizzard shad used the entire extent of restored habitat previously partially or completely inaccessible (Collier and Odom 1989).

As determined by total distance traveled and dams sites passed, connectivity among reaches appeared to increase in the Little River following dam removals. Collier and Odom (1989) did not provide information on the flows necessary to pass either the Cherry Hospital or Goldsboro water treatment plant dam and whether this dam was notched at the time. Considering the median water depth for American shad passage of the notched dam was present only 31% of the time in the springs of 2007 through 2010, passage of the two downstream dams prior to removal or notching was likely limited to very high flows and flooding. Even when intact dams were submerged, fish may not have passed. For example, Beasley and Hightower (2000) did not find any American shad implanted with telemetry transponders upstream of a low-head dam on the Neuse River during or after dam submergences; they did observe non-tagged American shad spawning upstream of the dam. Prior to removals, Rains Mill Dam apparently was the upstream extent for migratory fishes in
the Little River (Collier and Odom 1989). Numerous fish species, especially gizzard shad and American shad, migrated throughout the river including past Rains Mill and other former dam sites.

Increased connectivity in the Little River provided fish access to higher diversity habitat with fewer large predatory fish. Lower river habitat (rkm 0-13) was dominated by sand substrates. Habitat in the middle and upper reaches (rkm 13-82) was also dominated by sand, but contained a higher composition of coarse gravel through boulder and bedrock substrates. American shad and gizzard shad densities suggested they preferred the most upstream reaches, potentially using available coarse substrates as spawning habitat (Williamson and Nelson 1985; Beasley and Hightower 2000; Hightower et al. 2012).

Upstream reaches may also serve as a predation refuge. For example, Zeug and Winemiller (2007) found a negative relationship between gizzard shad and predator abundances in the Brazos River system, Texas. I captured very few large predatory fish at the upstream weir site in 2007. No tagged blue catfish and a limited number of tagged flathead catfish and channel catfish migrated into upstream reaches in 2010. Upstream reaches may also have an optimal combination of food availability and predation risk for American shad and gizzard shad fry and juveniles (Limburg 1996; Zeug and Winemiller 2008).

For fish restoration efforts, increased abundance is a primary goal for dam removals. In the Milwaukee River, Wisconsin, Kanehl et al. (1997) documented increased smallmouth bass Micropterus dolomieu abundance and biomass five years after dam removal while Burroughs et al. (2010) saw statistically significant, higher river-wide mean abundances for seven species and no significant declines post-removal for other species on a Michigan river.
No pre-removal data are available for the Little River, but this study provides baseline data for a potential follow-up study. Nearly 900 individuals were sampled at the most upstream dam removal site in 2007 and a total of 5,650 individuals were sampled in the springs of 2008 through 2010 at the lowermost dam removal site.

*Notched Dam Passage and Delay*

Apparent migratory impediments and delays at the Goldsboro water treatment notched dam suggest partial removals are less effective than complete dam removals. Based on detections upstream of the notched dam, passage ranged from 38% (blue catfish) to 85% (redhorses). It is possible individuals chose to remain downstream of the notched dam, potentially spawning, resting, or foraging. Also may migrations have been impeded or delayed during low flow conditions at other sites throughout the river, as river-wide captures and detections were low during these periods. Nature-like fishways have shown similar passage results. Bunt et al. (2011) found a mean of 75% and median of 86% successful passage for fish entering 21 nature-like fishways. Calles and Greenberg (2005) documented 90-100% of salmonids entering a nature-like fishway in a river in Sweden, with most fish passing during higher flows. Aarestrup et al. (2003) found around half of tagged sea trout *Salmo trutta* completely passed the nature-like passage in a Danish stream and suggested low flows factored into lower passage success.

Flow conditions and structural factors may influence notched dam passage and delays. Many individuals that passed did so in a prompt manner, typically during increasing or high flows. Yet, a noticeable proportion appeared to be delayed downstream for more
than one day, primarily during low flow periods. The concrete rubble spillway leading up to the notched dam was relatively short (~12.5 m) and the slope (~0.15 m/m) was steeper than many engineered nature-like fishways. For example, in a meta-analysis of fishways by Bunt et al. (2011) the mean slope of 21 nature-like fishways was 0.03 m/m. Detections indicate some individuals may have entered the notched dam spillway but failed to pass as they were detected at the notched dam antenna and then shortly thereafter at the downstream antenna. Sharp vertical increases (~0-0.5 m) leading up to the notched dam may present a challenge for migratory species but also small-bodied species. Velocity and turbulence may also limit passage by particular species or individuals under certain flow conditions.

Notched dam impediments decreases connectivity and access to upstream habitat, while delays may also negatively influence species. In particular, American shad rely on stored energy while in rivers and extended delays may lead to higher spawning mortalities (Leonard and McCormick 1999; Caudill et al. 2007) or spawning in unsuitable habitat (e.g., sand, silt). High concentrations of fish downstream of the notched dam could increase predation vulnerability (Schilt 2007). Both American shad and flathead catfish appeared to stage immediately downstream of the dam prior to upstream passage. However, flathead catfish appeared capable of passing the notched dam under all flow conditions, suggesting their downstream delays may be a choice (e.g., foraging) rather than forced.

**Fish Migrations**

River flow proved extremely important for fish migrations, and in turn, use of restored habitat in the Little River. The number of species and individuals sampled at the
fish weir increased during freshets following large precipitation events. Zitek et al. (2009) noted increased water levels resulted in high weir captures in Austria and Germany while Johnson and Noltie (1996) saw increased catches of longnose gar at their fish weir during freshets on a small Missouri river. Similarly, the number of anadromous and potamodromous PIT-tagged fish detected migrating and the upstream extent of migrations in the Little River also increased during freshets.

Flow may influence migrations in a number of ways. Increasing flows may serve as a migratory cue and assist fish (anadromous and potamodromous) in the Neuse River with locating the mouth of the Little River (Jonsson 1991; Jowett et al. 2005). Many gizzard shad and certain American shad migrated both directions during high flows in the Little River, potentially migrating as conditions at their current location became unsuitable or searching for optimal habitat (Zeug et al. 2009). Over a two-year study on the Neuse River, North Carolina, Burdick and Hightower (2006) collected a higher percentage of anadromous eggs and larvae in the higher flow year in restored upstream habitat with preferred spawning substrates. Higher turbidity and water depth during increased flows may provide a window to migrate with limited threat of predation (Jonsson 1991). It is also possible that increasing and high flows provided adequate water depth to pass man-made (i.e., notched dam) and natural (e.g., rock ledges, beaver dams, tree snags) obstructions (Beasley and Hightower 2000; Ovidio and Philippart 2002) commonly observed in the Little River during habitat surveys. River flow may also assist adults during emigrations (Jonsson 1991), as observed with high American shad emigration captures during 2008 and 2009 freshets. The top linear regression model included a quadratic term for gage height, suggesting migrations declined
at the highest flows. Fish may suspend migrations when flows exceed a certain point (e.g., swimming speed capabilities) or utilize the floodplain (Jonsson 1991; Haro et al. 2004). Alternatively, migration counts were artificially lower due to decreased weir and antenna effectiveness during the highest flow periods. Overall, migrations may be more influenced by flow conditions in smaller systems that experience greater fluctuations (e.g., Little River) than in more stable, deeper systems (Jonsson 1991).

Water temperature did not appear to have a direct relationship with daily migrations in the Little River, but likely influenced the timing of immigration and emigration (Jonsson 1991). For example, the optimal range for American shad spawning is 14 to 22 °C (Walburg and Nichols 1967; Hightower et al. 2012). Most American shad immigrated into the Little River during cooler temperatures, but emigrations, presumably after spawning, occurred when water temperatures reached 20 °C or above. American shad emigrations combined with mortalities (no longer detected) likely produced the significant, negative relationship between daily migrations and water temperature. In contrast, gizzard shad and flathead catfish migrations appeared less influenced by water temperature, at least during the spring.

**Migratory Fishes**

Fish passage and dam removal efforts often focus on restoring access to upstream spawning habitat for anadromous fish populations (Doyle et al. 2003; St. Pierre 2003; Burdick and Hightower 2006). American shad were the most abundant species captured at the weir in each year and used the entire extent of restored habitat. I collected a low density of American shad eggs and larvae (unpublished data) throughout Little River (rkm 11 - 72),
while Burdick and Hightower (2006) collected American shad eggs at rkm 11 in 2003 and 2004 and a very low density at rkm 41 in 2004. Hickory shad, striped bass, and blueback herring also passed at least the lowermost Little River dam removal in 2008 through 2010; I did not capture these species at the 2007 upstream weir site. The spring sampling periods commenced towards the end of hickory shad spawning periods, with the latest capture on April 4, 2008. Burdick and Hightower (2006) collected hickory shad eggs in the Little River in 2004 from rkm 11 to 26. The few blueback herring captures were surprising as their body size allowed passage through weir spacing. Striped bass appear to use the Little River sparingly, as only two individuals were captured at the weir and Burdick and Hightower (2006) did not collect their eggs in 2003 or 2004. Increased abundance of anadromous species would provide a greater influx of marine-derived prey that may benefit aquatic and terrestrial organisms residing in and near the Little River (Garman and Macko 1998).

Relatively little is known about the biology and migrations of gizzard shad in rivers. In the Little River, gizzard shad made extensive spring migrations (e.g., 2009 mean total distance traveled=71 rkm). Following dam removals on the Baraboo River, Wisconsin, Catalano et al. (2007) found gizzard shad recolonizing around 15 rkm of restored habitat. A highly concentrated upstream migration of gizzard shad occurred at the Little River weir during an April 2007 freshet. Similarly, antenna data showed gizzard shad ascended rapidly upstream during high flows and used upstream habitat at the highest rate of all species. Ricks et al. (2004) also had increased gizzard shad captures during freshets in April and May of 2003 at a steeppass fishway trap on a North Carolina tributary. In both tributaries, these could be spawning migrations as gizzard shad spawn in April through June and tend to
broadcast spawn as aggregates in shallow water; eggs are demersal and adhesive (Miller 1960; Williamson and Nelson 1985). Williamson and Nelson (1985) noted gizzard shad spawning activity was associated with rising water temperatures and water levels while embryo survival was highest in shallow reaches with clear flowing water and rocky substrates covered by periphyton. Reaches fitting this description were more common in middle and upper portions of the Little River. Zeug and Winemiller (2007) determined gizzard shad reproductive activity was related to the probability of flooding, and based on stable isotopes analyses, Zeug et al. (2009) suggested adult gizzard shad migrated into oxbow lakes during floods to spawn. The Little River extended into its floodplain multiple times throughout the spring study periods, but it is unknown if adult gizzard shad left the main channel or if desirable habitat is present in the floodplain. Gizzard shad are filter feeders, consuming plankton and detritus (Miller 1960; Williamson and Nelson 1985; Zeug et al. 2009), and potentially may migrate for foraging purposes. Based on weir captures and detections of individuals tagged in previous years, certain gizzard shad appeared to immigrate from the Neuse River while others may reside in the Little River year round. Gizzard shad, especially juveniles, are an important prey component in rivers and estuaries (Robertson et al. 2008; Overton et al. 2009), so an increased abundance of gizzard shad following dam removals may benefit predators.

Notchlip redhorses and shorthead redhorses were present throughout restored habitat in the Little River, but made shorter migrations than American shad and gizzard shad. Redhorses may not need to make extensive migrations as their preferred spawning habitat, coarse gravel and cobble bars (Jenkins and Burkhead 2004; Grabowski and Isely 2008),
existed in areas throughout the Little River. Therefore, relatively shorter migrations may take place between overwintering, spawning, and foraging habitats. Notchlip redhorses were active in late February and March, rarely detected in April and May, and then increased activity occurred for a few individuals in late May and early June. Shorthead redhorses were active in mid-March through mid-April, with a few individuals migrating at the end of May. Similar to gizzard shad, it appears that some redhorses may reside in the Little River year round, while others immigrate into the Little River in spring. Notchlip redhorses appeared to experience a mass mortality event in 2007. Many of the dead and live individuals captured moving downstream at the fish weir displayed a lack of scales and open flesh wounds on the ventral area of the caudal peduncle, eroded anal and caudal fins, and some individuals were decomposing and floating downstream. Redhorses disturb or create a depression in the substrate while depositing eggs and milt (Kwak and Skelly 1992; Grabowski and Isely 2008; Favrot 2009), and in the process may damage these areas of their body. These spawning stresses combined with high water temperatures during a drought year may have lead to the Little River mortality event. Favrot (2009) observed post-spawning mortality and decreased body condition of redhorses in 2007, particularly golden redhorse *Moxostoma erythrurum* in the Valley River, North Carolina. Sule and Skully (1985) attributed a few dead shorthead redhorse in Horse Creek, Illinois, to post-spawning mortality. Redhorses often have high biomass and may significantly impact ecosystems through grazing, nutrient cycling, serving as aquatic and terrestrial prey, and transporting mussel glochidia (Cooke et al. 2005).

All three of the large bodied catfish captured in the Little River were introduced into North Carolina from the Mississippi River Basin, but the obligate carnivore flathead catfish
are of the greatest concern to native fishes (Fuller 1999; Pine et al. 2005; Baumann and Kwak 2011). No flathead catfish were captured at the upstream Little River weir site in 2007, while at the downstream weir site only one was captured in 2008 but then substantial increases occurred in both 2009 and 2010. All flathead catfish appeared to immigrate from the Neuse River in the spring and emigrations appeared to commence in June. Flathead catfish displayed a high survival and return rate to the Little River, as 72% of individuals tagged in 2009 were recaptured or detected in 2010. Flathead catfish migrations were most extensive in 2010, with a few individuals reaching the most upstream reach (rkm 77-82). Channel catfish migrations were very similar while blue catfish remained in downstream reaches. These could be spawning migrations as all three species spawn in late spring and early summer (Jenkins and Burkhead 2004), but there is also the possibility that they are following prey items. At the fish weir, I documented four instances of flathead catfish predation on American shad in the Little River and Ashley and Buff (1987) documented cases in the Cape Fear River, North Carolina. Flathead catfish predation, especially when occurring prior to an American shad spawning, raises concern for restoration efforts in the Little River and wherever else flathead catfish now reside (Pine et al. 2005). Potential depredation effects may occur to other native fishes, as the large gape size of flathead catfish allows them to consume adult largemouth bass, gizzard shad, and bluegill (Slaughter and Jacobson 2008). Pine et al. (2005) determined flathead catfish predation was generally random (e.g., non-selective) in two North Carolina rivers as prey items included invertebrates, juvenile anadromous shad, and a total of eight fish families. Baumann and
Kwak (2011) also found a variety of prey items including seven different fish families in flathead catfish stomachs in the Cape Fear River basin, North Carolina.

_Gear Effectiveness_

The fish weir provided a singular location to capture and tag numerous individuals, but not without shortcomings on a system the size of the Little River. The fish weir fully blocked the river channel in low and some moderate flows, but captures in these periods were relatively lower as migratory fish had less motivation to enter cages to continue migrations. For example, during low flows I observed fish milling and American shad spawn splashes downstream of the weir. Zitek et al. (2009) had similar observations with their modified resistance board weir used in Austria and Germany. Catch rates were higher in the Little River during moderate to higher flows until a certain point when migrating fish clearly were missed due to gear failure and flooding that provided access around and over the submerged weir. Although I cannot quantitatively compare gears, despite non-functioning periods the fish weir was more effective at capturing American shad and catfishes while redhorses were capture more effectively via electrofishing. When evaluating habitat connectivity, Zitek et al. (2008) captured migrating species with fish traps not sampled with electrofishing.

Fish condition and survival to release were generally good and likely linked in part to the amount of visits and time spent at the fish weir, which was significant in this study but could be reduced if capturing only robust species (e.g., catfishes, suckers) or when downstream stranding does not occur. A larger or circular upstream cage, as used in aquaculture and transportation (Harris and Hightower 2011), may improve American shad
conditions and reduce upstream cage mortalities apparently due to fatigue and head damage (e.g., broken blood vessels, damaged eyes). The installation of a floating cage improved downstream migrating fish captures and reduced panel strandings that occurred most often in the evening and early night for all species. American shad and hickory shad were sometimes timid to enter the downstream cage, repeatedly swimming along the resistance board panels. Hickory shad often stranded but American shad more regularly entered the downstream cage.

Weir construction and installation were labor intensive with a steep initial learning curve while modifications improved functionality. Using pre-defined criteria (i.e., no modifications from Stewart (2002)) could speed up the construction process; Tobin (1994) fabricated two weirs over approximately 920 man-hours. Tobin (1994) recommended installation in areas with coarse substrates to limit scouring. These substrates were not present in lower reaches of the Little River and scouring of sand was an issue along the I-beam. Scouring likely was a factor in the resistance board section washing downstream in 2009. Additional sandbags and longer rebar held the weir in place in 2010. I cleared debris between PVC pickets by walking and jumping on panels to dislodge items, keeping panels floating until water levels were too high and fully submerged the panels. Sand scouring and debris buildup was also an issue along the picket weir and upstream cage, sometimes resulting in significant leaning or collapsing. I remedied this by installing pickets at a nearly 90° vertical angle with multiple metal, downstream supports, placing sandbags in front and behind the bottom of pickets to limit scouring, and regularly removing debris.

The PIT antennas passively and continuously monitored tagged fish to provide valuable information, but also had issues in part due to the size of the Little River. The use
of PIT antennas has increased substantially (Castro-Santos et al. 1996; Zydlewski et al. 2006; Hewitt et al. 2010), but my antennas had larger dimensions than most previous studies. My small antennas (<11 m wide) had higher detection ranges than larger antennas (14–22 m wide). Missed detections were likely minimal during low and moderate flows when fewer fish migrated. Higher flows led to fish movement and numerous detections, but with more missed detections as antennas became out of tune or as fish swam outside of the detection range. Synthetic cable tightened by ratchet straps decreased downstream bowing, improving antenna functionality in higher flows. Installing both antenna lines on the river bottom (“flat plate” antenna) would further decrease bowing of the top line, but with the trade-off of only detecting fish in close proximity to the antenna (Zydlewski et al. 2006). Other potential sources of error (missed tagged fish) include the orientation of the fish relative to the antenna, the swimming speed of the fish, and multiple fish in the antenna detection field at the same time (Zydlewski et al. 2006; Aymes and Rives 2009).

Seasonal PIT antenna detection rates varied by antenna, year, and species. Excluding the notched dam antenna, antennas were installed early in 2010 and functioned reasonably well with seasonal detection rates ranging from 70 to 100%. These are coarse estimates as successive detections at an antenna were excluded and subsequent antennas were spaced far apart. It is difficult to compare these estimates to other studies given varying antenna equipment and dimensions, transponders, species, conditions, and study durations, but they are in the same general range with reported values of 67 to 97% (Castro-Santos et al. 1996; Zydlewski et al 2001; Aarestrup et al. 2003; Adams et al. 2006; Aymes and Rives 2009).
The PIT antennas greatly increased overall recapture efficiency, but at a coarse spatial scale. The antennas detected individuals multiple times in a season and individuals tagged in previous years that were not sampled at the weir. Hewitt et al. (2010) documented a substantial increase in recapture efficiency of Lost River suckers *Deltistes luxatus* when using PIT antennas compared to traditional sampling methods. However, a number of individuals were never recaptured or detected in the Little River, apparently perishing due to handling or tagging stresses. Alternatively, these individuals may have simply been missed at the weir and antennas or did not migrate enough to be detected. American shad and hickory shad appeared the most vulnerable (30 to 72%) to potential tagging stress and mortality while catfishes were more robust (0 to 14%). The PIT antenna array provided coarse scale information on migrations and habitat use. For example, a long gap (32 rkm) occurred between the Forest Service and Rains Crossroads antennas due to wide, non-uniform river channels at the limited access points. Therefore, I used the Rains Crossroads antenna as a proxy for fish passage of the Rains Mill dam removal site. I could not locate preferred habitat (e.g., spawning grounds) given the coarse scale of the antenna array. I did fabricate a portable PIT antenna, used successfully in other studies to manually relocate tagged fish and assess microhabitat (Zydlewski et al. 2001), but did not conduct extensive searches given the time it would take to cover large river reaches with a short read range (~1.0 m) and the necessity to attend the fish weir. While the PIT antennas have setbacks including a coarse scale, the data can be used in capture-recapture modeling to address additional questions including survival (Hewitt et al. 2010).
Implications

Overall, the fish weir and PIT technology were useful gears, allowing me to document migratory fish species use of habitat restored by dam removals in the Little River, show the importance of flow for migrations, and increase information on migratory fishes. The main trade-offs were extensive labor and decreased effectiveness in high flows, indicating the size and flow regime of the Little River may be at the upper extent of their utility. Multiple fish species, especially American shad and gizzard shad, migrated into the upper reaches of restored habitat that may be important spawning and nursery grounds with fewer large predators. While a large proportion of individuals passed the Goldsboro water treatment plant notched dam, apparent impediments and delays especially at lower flows decreases connectivity and access to upstream habitat and may increase energy expenditures and vulnerability to predation. The increasing abundance and migratory extent of introduced flathead catfish and their documented predation on American shad is a cause for concern. River flow, often regulated at large dams, proved very important in the Little River for fish migrations, passage of the notched dam, and therefore the use of restored habitat. The ultimate restoration goal is to increase native fish abundance, so a follow-up Little River study would be very informative. Future studies should conduct thorough pre- and post-dam removal assessments, and when possible conduct concurrent studies on similar rivers to help evaluate whether responses are due to dam removals or temporal and environmental variation. Nevertheless, this study contributes to the emerging science of dam removals and provides evidence that complete removal of derelict dams is beneficial to migratory fish species.
REFERENCES


Table 2.1. Weir captures by species and year at the Little River fish weir located at rkm 56 in 2007 and rkm 4 in 2008-2010. Migratory species denoted as anadromous or semi-anadromous (*), catadromous (+), and potamodromous (°).

<table>
<thead>
<tr>
<th>Common name</th>
<th>Scientific name</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>American eel*</td>
<td><em>Anguilla rostrata</em></td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>1</td>
</tr>
<tr>
<td>blueback herring</td>
<td><em>Alosa aestivalis</em></td>
<td>.</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>hickory shad*</td>
<td><em>Alosa mediocris</em></td>
<td>.</td>
<td>113</td>
<td>1</td>
<td>79</td>
</tr>
<tr>
<td>American shad*</td>
<td><em>Alosa sapidissima</em></td>
<td>488</td>
<td>1121</td>
<td>2064</td>
<td>1072</td>
</tr>
<tr>
<td>brown bullhead</td>
<td><em>Ameiurus nebulosus</em></td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>bowfin</td>
<td><em>Amia calva</em></td>
<td>1</td>
<td>3</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>flier</td>
<td><em>Centrarchus macropterus</em></td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>1</td>
</tr>
<tr>
<td>common carp</td>
<td><em>Cyprinus carpio</em></td>
<td>.</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>gizzard shad*</td>
<td><em>Dorosoma cepedianum</em></td>
<td>294</td>
<td>59</td>
<td>125</td>
<td>148</td>
</tr>
<tr>
<td>creek chubsucker</td>
<td><em>Erimyzon oblongus</em></td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>7</td>
</tr>
<tr>
<td>redfin pickerel</td>
<td><em>Esox americanus</em></td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>chain pickerel</td>
<td><em>Esox niger</em></td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>3</td>
</tr>
<tr>
<td>blue catfish*</td>
<td><em>Ictalurus furcatus</em></td>
<td>.</td>
<td>3</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>channel catfish*</td>
<td><em>Ictalurus punctatus</em></td>
<td>2</td>
<td>79</td>
<td>112</td>
<td>94</td>
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<tr>
<td>longnose gar</td>
<td><em>Lepisosteus osseus</em></td>
<td>1</td>
<td>27</td>
<td>180</td>
<td>71</td>
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<tr>
<td>rebreast sunfish</td>
<td><em>Lepomis auritus</em></td>
<td>.</td>
<td>2</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>pumpkinseed</td>
<td><em>Lepomis gibbosus</em></td>
<td>.</td>
<td>1</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>bluegill</td>
<td><em>Lepomis macrochirus</em></td>
<td>.</td>
<td>1</td>
<td>15</td>
<td>38</td>
</tr>
<tr>
<td>redear sunfish</td>
<td><em>Lepomis microlophus</em></td>
<td>.</td>
<td>.</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>largemouth bass</td>
<td><em>Micropterus salmoides</em></td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>white perch*</td>
<td><em>Morone americana</em></td>
<td>.</td>
<td>1</td>
<td>1</td>
<td>.</td>
</tr>
<tr>
<td>striped bass*</td>
<td><em>Morone saxatilis</em></td>
<td>.</td>
<td>1</td>
<td>1</td>
<td>.</td>
</tr>
<tr>
<td>notchlip redhorse*</td>
<td><em>Moxostoma collapsum</em></td>
<td>58</td>
<td>3</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>shorthead redhorse*</td>
<td><em>Moxostoma macrolepidotum</em></td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>bull chub</td>
<td><em>Nocomis raneyi</em></td>
<td>6</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>black crappie</td>
<td><em>Pomoxis nigromaculatus</em></td>
<td>2</td>
<td>18</td>
<td>21</td>
<td>59</td>
</tr>
<tr>
<td>flathead catfish*</td>
<td><em>Pylodecitis olivaris</em></td>
<td>.</td>
<td>1</td>
<td>81</td>
<td>166</td>
</tr>
<tr>
<td>black jumprock</td>
<td><em>Scartomyzon cervinus</em></td>
<td>1</td>
<td>.</td>
<td>.</td>
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<tr>
<td>sunfish group</td>
<td><em>Lepomis spp.</em></td>
<td>14</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>decomposing redhorse</td>
<td><em>Moxostoma spp.</em></td>
<td>2</td>
<td>.</td>
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</tr>
<tr>
<td>unidentified chub</td>
<td><em>Nocomis sp.</em></td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>6829</td>
<td>879</td>
<td>1448</td>
<td>2694</td>
</tr>
<tr>
<td>Species Richness</td>
<td></td>
<td>28</td>
<td>14+</td>
<td>19</td>
<td>19</td>
</tr>
</tbody>
</table>
Table 2.2. Species and number of individuals receiving PIT transponders from 2008 to 2010 in the Little River.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>American shad</td>
<td>97</td>
<td>602</td>
<td>417</td>
<td>860</td>
<td>773</td>
<td>2</td>
<td>2751</td>
</tr>
<tr>
<td>Blue catfish</td>
<td>-</td>
<td>-</td>
<td>11</td>
<td>11</td>
<td>-</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Creek chubsucker</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>11</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Channel catfish</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>64</td>
<td>-</td>
<td>69</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>1</td>
<td>71</td>
<td>149</td>
<td>221</td>
<td>-</td>
<td>-</td>
<td>221</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>4</td>
<td>108</td>
<td>123</td>
<td>235</td>
<td>-</td>
<td>-</td>
<td>235</td>
</tr>
<tr>
<td>Hickory shad</td>
<td>20</td>
<td>29</td>
<td>49</td>
<td>-</td>
<td>49</td>
<td>-</td>
<td>49</td>
</tr>
<tr>
<td>Notchlip redhorse</td>
<td>3</td>
<td>11</td>
<td>3</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Shorthead redhorse</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>White perch</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>18</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>126</td>
<td>602</td>
<td>613</td>
<td>861</td>
<td>1162</td>
<td>3</td>
<td>3367</td>
</tr>
</tbody>
</table>

Table 2.3. Percent (total number) mortality and fallback (individuals recaptured within 24 hours) at the Little River fish weir from 2007 through 2010. Downstream mortalities included individuals removed from downstream cage or stranded on fish weir panels.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upstream mortality</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American shad</td>
<td>31.1% (45)</td>
<td>24.3% (136)</td>
<td>7.7% (471)</td>
<td>4.4% (856)</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>1.5% (260)</td>
<td>0.0% (53)</td>
<td>0.0% (116)</td>
<td>0.8% (134)</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>-</td>
<td>0.0% (1)</td>
<td>1.3% (78)</td>
<td>0.0% (154)</td>
</tr>
<tr>
<td>Other species</td>
<td>7.1% (14)</td>
<td>4.4% (69)</td>
<td>0.0% (346)</td>
<td>0.3% (345)</td>
</tr>
<tr>
<td><strong>Downstream mortality</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American shad</td>
<td>20.7% (440)</td>
<td>23.0% (1004)</td>
<td>13.5% (1726)</td>
<td>38.4% (384)</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>47.3% (36)</td>
<td>57.1% (7)</td>
<td>28.6% (14)</td>
<td>42.3% (26)</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>-</td>
<td>20.0% (10)</td>
<td>0.0% (6)</td>
<td></td>
</tr>
<tr>
<td>Other species</td>
<td>74.7% (75)</td>
<td>35.5% (203)</td>
<td>7.2% (83)</td>
<td>26.5% (102)</td>
</tr>
<tr>
<td><strong>Fallback</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American shad</td>
<td>27.6% (29)</td>
<td>15.5% (97)</td>
<td>12.7% (417)</td>
<td>9.3% (775)</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>-</td>
<td>25.0% (4)</td>
<td>0.9% (109)</td>
<td>8.9% (123)</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>-</td>
<td>0.0% (1)</td>
<td>6.9% (72)</td>
<td>4.0% (149)</td>
</tr>
</tbody>
</table>
Table 2.4. Total downstream captures at the Little River in 2008 to 2010, including fish captured in a downstream floating cage and those stranded on weir panels. Cage capture compared to stranding (cage:panel) and survival to release varied by species and year.

<table>
<thead>
<tr>
<th></th>
<th>Total captures</th>
<th>Cage:panel captures</th>
<th>Survival</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cage</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td>2008</td>
</tr>
<tr>
<td>American shad</td>
<td>1141</td>
<td>4.00</td>
<td>81.5%</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>60</td>
<td>19.00</td>
<td>98.2%</td>
</tr>
<tr>
<td>Hickory shad</td>
<td>118</td>
<td>1.03</td>
<td>81.7%</td>
</tr>
<tr>
<td>Other species</td>
<td>134</td>
<td>8.57</td>
<td>89.2%</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>American shad</td>
<td>1722</td>
<td>1.41</td>
<td>93.1%</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>15</td>
<td>0.88</td>
<td>100.0%</td>
</tr>
<tr>
<td>Hickory shad</td>
<td>1</td>
<td>0.00</td>
<td>0.0%</td>
</tr>
<tr>
<td>Other species</td>
<td>59</td>
<td>4.36</td>
<td>95.8%</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>American shad</td>
<td>384</td>
<td>1.30</td>
<td>78.3%</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>26</td>
<td>0.18</td>
<td>100.0%</td>
</tr>
<tr>
<td>Hickory shad</td>
<td>55</td>
<td>0.15</td>
<td>71.4%</td>
</tr>
<tr>
<td>Other species</td>
<td>22</td>
<td>3.40</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 2.5. Dimensions and transponder detection read range for seven PIT antennas installed on the Little River recorded near the end of the 2010 sampling season.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Antenna dimensions (m)</th>
<th>Antenna read range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>Depth</td>
</tr>
<tr>
<td>Downstream ND</td>
<td>20.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Notched dam</td>
<td>14.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Forest Service</td>
<td>17.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Rains Crossroads</td>
<td>21.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Lowell Mill</td>
<td>16.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Shoeheel Road</td>
<td>10.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Old Dam Road</td>
<td>10.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Table 2.6. Seasonal detection rates by species and year (number of tagged individuals) for seven Little River PIT antennas; includes poorly and non-functioning periods.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>American shad</th>
<th>Gizzard shad</th>
<th>Flathead catfish</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009 (195)</td>
<td>2010 (441)</td>
<td>2009 (74)</td>
</tr>
<tr>
<td></td>
<td>Possible Rate</td>
<td>Possible Rate</td>
<td>Possible Rate</td>
</tr>
<tr>
<td>Downstream ND</td>
<td>261 0.80</td>
<td>511 0.84</td>
<td>85 0.56</td>
</tr>
<tr>
<td>Notched dam</td>
<td>209 0.76</td>
<td>406 0.17</td>
<td>74 0.54</td>
</tr>
<tr>
<td>Forest Service</td>
<td>157 0.82</td>
<td>372 0.95</td>
<td>63 0.43</td>
</tr>
<tr>
<td>Rains Crossroads</td>
<td>60 0.20</td>
<td>222 0.73</td>
<td>45 0.16</td>
</tr>
<tr>
<td>Lowell Mill</td>
<td>55 0.78</td>
<td>188 0.70</td>
<td>60 0.40</td>
</tr>
<tr>
<td>Shoeheel Road</td>
<td>37 0.76</td>
<td>123 0.94</td>
<td>59 0.39</td>
</tr>
<tr>
<td>Old Dam Road</td>
<td>24 -</td>
<td>96 -</td>
<td>54 -</td>
</tr>
</tbody>
</table>

Table 2.7. Percent (total number) of tagged individuals that were never recaptured or detected at an antenna in the Little River from 2008 through 2010. This is a maximum estimate of tagging mortality.

<table>
<thead>
<tr>
<th>Species</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>American shad</td>
<td>41.2%</td>
<td>34.5%</td>
<td>30.0%</td>
</tr>
<tr>
<td>Blue catfish</td>
<td>-</td>
<td>-</td>
<td>27.3%</td>
</tr>
<tr>
<td>Channel catfish</td>
<td>-</td>
<td>0.0%</td>
<td>14.1%</td>
</tr>
<tr>
<td>Creek chubsucker</td>
<td>-</td>
<td>-</td>
<td>0.0%</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>0.0%</td>
<td>8.3%</td>
<td>10.7%</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>100.0%</td>
<td>32.1%</td>
<td>16.3%</td>
</tr>
<tr>
<td>Hickory shad</td>
<td>57.9%</td>
<td>-</td>
<td>72.4%</td>
</tr>
<tr>
<td>Notchlip redhorse</td>
<td>66.7%</td>
<td>75.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Shorthead redhorse</td>
<td>85.7%</td>
<td>100.0%</td>
<td>16.7%</td>
</tr>
</tbody>
</table>
Table 2.8. Mean total distance traveled and number of times dam sites were passed by tagged individuals in the Little River in springs of 2009 and 2010. Note: individuals detected at Rains Crossroads antenna (rkm 44) assumed to pass the former Rains Mill Dam site.

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>Total distance traveled Mean ± SE (rkm)</th>
<th>Total dam sites passed</th>
<th>Cherry Hospital (rm 3.8)</th>
<th>Goldsboro (rkm 7.9)</th>
<th>Rains Mill (rkm 37.7)</th>
<th>Lowell Mill (rkm 56.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 American shad</td>
<td>126</td>
<td>39.9 ± 3.00 (161)</td>
<td>3.42 (9)</td>
<td>1.11 (2)</td>
<td>1.40 (5)</td>
<td>0.48 (3)</td>
<td>0.44 (4)</td>
</tr>
<tr>
<td>2010 American shad</td>
<td>317</td>
<td>47.0 ± 1.96 (156)</td>
<td>3.49 (11)</td>
<td>1.03 (2)</td>
<td>1.17 (5)</td>
<td>0.70 (4)</td>
<td>0.59 (4)</td>
</tr>
<tr>
<td>2009 Gizzard shad</td>
<td>53</td>
<td>71.0 ± 6.54 (161)</td>
<td>4.16 (9)</td>
<td>1.01 (2)</td>
<td>0.65 (4)</td>
<td>0.39 (3)</td>
<td>0.53 (4)</td>
</tr>
<tr>
<td>2010 Gizzard shad</td>
<td>103</td>
<td>70.0 ± 6.72 (257)</td>
<td>4.57 (16)</td>
<td>0.79 (2)</td>
<td>1.37 (7)</td>
<td>1.20 (6)</td>
<td>1.21 (7)</td>
</tr>
<tr>
<td>2009 Flathead catfish</td>
<td>34</td>
<td>16.4 ± 1.76 (56)</td>
<td>2.24 (4)</td>
<td>1.06 (3)</td>
<td>1.06 (2)</td>
<td>0.06 (1)</td>
<td>0.06 (1)</td>
</tr>
<tr>
<td>2010 Flathead catfish</td>
<td>139</td>
<td>28.0 ± 2.47 (150)</td>
<td>2.86 (8)</td>
<td>1.10 (3)</td>
<td>1.16 (3)</td>
<td>0.32 (2)</td>
<td>0.28 (4)</td>
</tr>
</tbody>
</table>

Table 2.9. Cumulative distribution of PIT-tagged individuals that migrated through or into eight different Little River reaches. All individuals were detected at one or more antennas.

<table>
<thead>
<tr>
<th>Reach</th>
<th>American shad</th>
<th>Gizzard shad</th>
<th>Flathead catfish</th>
<th>Channel catfish</th>
<th>Blue catfish</th>
<th>Redhorses</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>43</td>
<td>195</td>
<td>441</td>
<td>73</td>
<td>126</td>
<td>57</td>
</tr>
<tr>
<td>Cherry Hospital</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Downstream ND</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Notched Dam (ND)</td>
<td>0.74</td>
<td>0.77</td>
<td>0.82</td>
<td>0.83</td>
<td>0.72</td>
<td>0.75</td>
</tr>
<tr>
<td>Forest Service</td>
<td>0.65</td>
<td>0.72</td>
<td>0.73</td>
<td>0.82</td>
<td>0.60</td>
<td>0.72</td>
</tr>
<tr>
<td>Rains Crossroads</td>
<td>0.26</td>
<td>0.39</td>
<td>0.49</td>
<td>0.49</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Lowell Mill</td>
<td>0.23</td>
<td>0.24</td>
<td>0.31</td>
<td>0.49</td>
<td>0.45</td>
<td>0.11</td>
</tr>
<tr>
<td>Shoeheel Road</td>
<td>0.14</td>
<td>0.20</td>
<td>0.45</td>
<td>0.37</td>
<td>0.00</td>
<td>0.07</td>
</tr>
<tr>
<td>Old Dam Road</td>
<td>0.08</td>
<td>0.15</td>
<td>0.44</td>
<td>0.32</td>
<td>0.00</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 2.10. Dimensions and habitat characteristics of eight reaches in the Little River, divided according to location of weir and PIT antennas. Substrate embeddedness indicates the degree coarse substrates (gravel and larger) were surrounded by fine substrate.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Start (rkm)</th>
<th>Length (rkm)</th>
<th>Width (m)</th>
<th>Area (ha)</th>
<th>Habitat type (proportion)</th>
<th>Substrate Embedded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouth - Cherry Hospital</td>
<td>0</td>
<td>3.8</td>
<td>23.8</td>
<td>9.1</td>
<td>0.26 0.41 0.33</td>
<td>3.72</td>
</tr>
<tr>
<td>Cherry Hospital - Notched Dam</td>
<td>3.7</td>
<td>3.9</td>
<td>26.7</td>
<td>10.4</td>
<td>0.13 0.45 0.42</td>
<td>3.71</td>
</tr>
<tr>
<td>Notched Dam - Forest Service</td>
<td>7.7</td>
<td>5.7</td>
<td>21.0</td>
<td>12.0</td>
<td>0.01 0.66 0.33</td>
<td>3.37</td>
</tr>
<tr>
<td>Forest Service - Rains Crossroads</td>
<td>13.4</td>
<td>31.9</td>
<td>24.4</td>
<td>77.8</td>
<td>0.13 0.33 0.54</td>
<td>2.98</td>
</tr>
<tr>
<td>Rains Crossroads - Lowell Mill</td>
<td>45.3</td>
<td>11.1</td>
<td>21.2</td>
<td>23.6</td>
<td>0.15 0.52 0.33</td>
<td>2.84</td>
</tr>
<tr>
<td>Lowell Mill - Shoeheel Road</td>
<td>56.4</td>
<td>15.6</td>
<td>21.2</td>
<td>33.1</td>
<td>0.19 0.57 0.24</td>
<td>3.18</td>
</tr>
<tr>
<td>Shoeheel Road - Old Dam Road</td>
<td>72.0</td>
<td>5.0</td>
<td>15.8</td>
<td>7.9</td>
<td>0.10 0.55 0.34</td>
<td>3.03</td>
</tr>
<tr>
<td>Old Dam Road - Atkinson Mill</td>
<td>77.0</td>
<td>5.3</td>
<td>19.1</td>
<td>10.1</td>
<td>0.02 0.64 0.34</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Table 2.11. Total migratory delay and duration of the staging period downstream of the notched dam (rkm 8) by three species in the Little River during the springs of 2009 and 2010 when the notched dam antenna functioned properly.

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>Total delay (days)</th>
<th>Stage period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean ± SE</td>
<td>Min</td>
</tr>
<tr>
<td>2009 American shad</td>
<td>64</td>
<td>1.8 ± 0.37</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>2010 American shad</td>
<td>20</td>
<td>1.1 ± 0.63</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>2009 Gizzard shad</td>
<td>18</td>
<td>4.1 ± 1.46</td>
<td>0.04</td>
</tr>
<tr>
<td>2010 Gizzard shad</td>
<td>11</td>
<td>3.6 ± 3.38</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>2009 Flathead catfish</td>
<td>23</td>
<td>2.0 ± 0.43</td>
<td>0.04</td>
</tr>
<tr>
<td>2010 Flathead catfish</td>
<td>13</td>
<td>1.3 ± 0.51</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Table 2.12. Detection durations at an antenna immediately downstream of the notched dam (rkm 8) for fish that either passed or never passed the structure in the Little River during the springs of 2009 and 2010.

<table>
<thead>
<tr>
<th>Species</th>
<th>Downstream delay (days) prior to passage</th>
<th>Downstream duration (days), never passed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean ± SE</td>
</tr>
<tr>
<td>2009 American shad</td>
<td>103</td>
<td>0.9 ± 0.21</td>
</tr>
<tr>
<td>2010 American shad</td>
<td>257</td>
<td>0.8 ± 0.11</td>
</tr>
<tr>
<td>2009 Gizzard shad</td>
<td>18</td>
<td>4.2 ± 1.46</td>
</tr>
<tr>
<td>2010 Gizzard shad</td>
<td>86</td>
<td>1.8 ± 0.55</td>
</tr>
<tr>
<td>2009 Flathead catfish</td>
<td>29</td>
<td>1.6 ± 0.80</td>
</tr>
<tr>
<td>2010 Flathead catfish</td>
<td>136</td>
<td>2.0 ± 0.40</td>
</tr>
</tbody>
</table>

Table 2.13. Descriptive statistics of the estimated maximum water depth present when individuals from three different species successfully passed the Little River notched dam in the spring of 2010 and the proportion of time these depths were available.

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>Min (mm)</th>
<th>Mean ± SE (mm)</th>
<th>Median (mm)</th>
<th>Spring 2009-2010</th>
<th>Spring 2007-2010</th>
<th>2007-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Mean ± SE</td>
<td>Median</td>
<td>Min Median</td>
<td>Min Median</td>
<td>Min Median</td>
</tr>
<tr>
<td>American shad</td>
<td>100</td>
<td>297.8</td>
<td>653.4 ± 17.35</td>
<td>713.8</td>
<td>0.94 0.39</td>
<td>0.90 0.31</td>
<td>0.60 0.19</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>33</td>
<td>362.6</td>
<td>720.7 ± 29.94</td>
<td>785.4</td>
<td>0.85 0.32</td>
<td>0.81 0.25</td>
<td>0.52 0.14</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>41</td>
<td>200.1</td>
<td>601.0 ± 35.1</td>
<td>517.8</td>
<td>0.99 0.65</td>
<td>0.98 0.55</td>
<td>0.72 0.36</td>
</tr>
</tbody>
</table>

Table 2.14. Top single and multiple predictor linear regression models for the daily number of individuals captured or detected compared to different environmental variables in the Little River in 2010.

<table>
<thead>
<tr>
<th>Species</th>
<th>AIC&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>AIC&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>AIC&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>AIC&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>American shad</td>
<td>384.7</td>
<td>0.333</td>
<td>Princeton gage, gage&lt;sup&gt;2&lt;/sup&gt;</td>
<td>385.8</td>
<td>0.325</td>
<td>Temperature</td>
<td>393.6</td>
<td>0.248</td>
</tr>
<tr>
<td>Gizzard shad</td>
<td>292.6</td>
<td>0.594</td>
<td>Princeton gage, gage&lt;sup&gt;2&lt;/sup&gt;</td>
<td>241.4</td>
<td>0.767</td>
<td>Temperature</td>
<td>369.6</td>
<td>0.040</td>
</tr>
<tr>
<td>Flathead catfish</td>
<td>297.5</td>
<td>0.505</td>
<td>Princeton gage, gage&lt;sup&gt;2&lt;/sup&gt;</td>
<td>283.4</td>
<td>0.576</td>
<td>Temperature</td>
<td>359.9</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Model: Princeton gage, gage<sup>2</sup>, temperature, calendar date

American shad 331.2 0.645
Gizzard shad 244.0 0.772
Flathead catfish 270.4 0.649
Figure 2.1. Map of the Little River, North Carolina, depicting dam locations and status (year removed, notched, present) and passive integrated transponder (PIT) antennas in 2009-2010. The fish weir was located at rkm 56 in 2007 and rkm 4 in 2008-2010.
Figure 2.2. Locations of fish collected via electrofishing the Little River on April 24 and May 4, 2007. American shad were more common in the upstream reach, while notchlip redhorse were more common in the lower portion of the upstream reach and the upper portion of the downstream reach.
Figure 2.3. Spring hydrographs of Little River flow (USGS gage 02088500) and dates the fish weir functioned properly (black boxes) by completely blocking the river channel and water column in 2007 through 2010.
Figure 2.4. Name and location (rkm) of Little River PIT antennas and dates they functioned in springs of 2008 through 2010.
Figure 2.5. Examples of fish migrating long distances and past partially and completely removed dam sites in the Little River in 2010. The American shad traveled 127 rkm and passed dam sites 11 times while the gizzard shad traveled 238 rkm and passed dam sites 14 times. Note: assume fish detected at rkm 44 antenna migrated past rkm 38 dam removal site.
Figure 2.6. Example of cumulative fish distributions relative to removed, partially removed, and present dams on the Little River in 2010. All three species displayed a noticeable decline at the notched dam, and then a linear decline with increasing upstream distance.

Figure 2.7. Example of fish density based on their maximum extent of migration relative to reach location and area for three migratory fish species in the Little River in 2010.
Figure 2.8. Dominant substrate (top) and sub-dominant substrate (bottom) in eight different Little River reaches. Habitat complexity (e.g., number of substrate classes, coarser substrates) increased upstream of rkm 13.
Figure 2.9. Examples of American shad patterns exhibited upon reaching the notched dam (rkm 7.9, dashed line) in the Little River. Certain individuals reached the notched dam and returned to the weir (a) or were never detected elsewhere (b). Others reached the structure, attempted to pass but apparently failed (c) or passed under higher flow conditions (d). Some individuals were delayed for substantial periods during low flows until passing during a freshet (e). Others individuals reached the structure during freshets and passed rapidly (f).
Figure 2.10. Simple logistic regression predicted that the relative probability of American shad ($p<0.001$), gizzard shad ($p=0.006$), and flathead catfish ($p=0.777$) notched dam passage increased with increasing water depth. Individual species plots compare the observed data points (0=detected immediately downstream, 1=detected successfully passing; offset for visualization) to the predicted points.
Figure 2.11. Fish captures (all species) at the Little River fish weir (rkm 56) in 2007 compared to water temperature and flow. A large upstream gizzard shad migration occurred during an April freshet while American shad dominated downstream migrations in late April and early May when water temperatures exceeded 20 °C.
Figure 2.12. Fish captures (all species) at the Little River fish weir (rkm 4) in 2008-2010 compared to water temperature and flow. Large American shad emigrations occurred during freshets in 2008 and 2009 but not in 2010. Both upstream and downstream fish captures increased during freshets in 2010. Note: scales differ between years.
Figure 2.13. Daily detections of three PIT-tagged migratory fish species at the Forest Service antenna (rkm 13) compared to water temperature and flow in the Little River in 2010.

Figure 2.14. Daily detections of three PIT-tagged migratory fish species at the Forest Service antenna (rkm 13) compared to water temperature and flow in the Little River in 2010.
Figure 2.15. Linear regressions comparing the number of daily captures and PIT antenna detections for American shad, gizzard shad, and flathead catfish compared to different predictor variables (each includes quadratic term). River flow condition metrics proved to be the best predictors of daily fish migrations.
CHAPTER 3

American Shad Migratory Behavior, Weight Loss, Survival, and Abundance Following Dam Removals and Flathead Catfish Introductions

ABSTRACT

Despite extensive management and research, American shad *Alosa sapidissima* populations have experienced prolonged population declines, and uncertainty about underlying mechanisms remains. In the springs of 2007 through 2010, I used a resistance board weir and passive integrated transponder (PIT) technology to capture, tag, and track American shad in the Little River, North Carolina. Complete and partial low-head dam removals have occurred in this tributary to the Neuse River where flathead catfish *Pylodictis olivaris* were introduced approximately 25 years ago. My objectives were to examine migratory behaviors and estimate weight loss, seasonal survival, abundance, and predation by flathead catfish. During freshets, American shad weir captures increased, migrations were more extensive and rapid, and diel activity shifted to daytime hours. Weight loss displayed a positive relationship with cumulative temperature during residence. Emigrating males lost 30% or less of their initial weight compared to 50% or less for females, indicating potential survival thresholds. Spawning season survival estimates ranged from 0.07 to 0.17; no distinct factors (e.g., sex, size, migrations) contributing to survival were documented. American shad abundance increased from 2007 through 2009, but was lower in 2010. Flathead catfish were most common in May and in lower reaches, displayed increasing annual abundance, and consumed an estimated 237 to 1,278 American shad (7-36% of estimated run size) in 2010. This substantial new American shad spawning information should aid in restoration efforts.
INTRODUCTION

Anadromous American shad *Alosa sapidissima* have experienced drastic and prolonged population declines in their native range despite extensive management and research efforts. Native to the Atlantic coast of North America, with spawning migrations ranging from the St. Johns River, Florida to the St. Lawrence River, Canada, American shad ecologically connect oceans, estuaries, and rivers by transporting nutrients while functioning as both predators and prey (Leggett and Whitney 1972; Garman and Macko 1998; Limburg 2003). American shad were historically abundant, supporting important commercial fisheries with coastwide landings exceeding 20,000 metric tons in the late 1890s, but have declined dramatically to present landings in the hundreds of metric tons (Walburg and Nichols 1967; Hightower et al. 1996; Limburg 2003).

Efforts to restore American shad populations focus on anthropogenic factors typically attributed to their declines, in particular overfishing, habitat degradation, and habitat loss due to dams (Hightower et al. 1996; Cooke and Leach 2003; St. Pierre 2003). To reduce overfishing, agencies have implemented stricter harvest regulations, including eliminating the ocean-intercept fishery and a Virginia moratorium in the Chesapeake Bay system (Olney and Hoenig 2001; ASMFC 2007). Extensive larvae stocking programs are intended to offset decreased egg and larval production due to low spawning stocks or degraded spawning and nursery habitat (Hendricks 2003; St. Pierre 2003; Olney et al. 2003). Providing fish passage, transporting adults, and removing dams are three methods to reconnect access to historic spawning grounds (Hendricks 2003; St. Pierre 2003; Cooke and Leach 2003; Burdick and Hightower 2006). Signs of success include return of hatchery-reared fish, increased passage
rates and extent of upstream migrations, and populations increasing from extremely low
numbers (Cooke and Leach 2003; Olney et al. 2003; St. Pierre 2003; Burdick and Hightower
2006; Raabe, Chapter 2).

Although restoration efforts have shown signs of success, American shad populations
remain at historically low levels (Limburg 2003; ASMFC 2007; Limburg and Walden 2009),
and fundamental questions about underlying mechanisms remain unanswered. Prior to dam
constructions, American shad migrated up to hundreds of kilometers upriver to reach
spawning grounds (Stevenson 1899). However, the proportion that migrated these great
distances is unknown as are the present distributions of spawning American shad in many
rivers. Similarly, the extent of populations that remain impeded by either man-made or
natural obstructions warrants further study (Beasley and Hightower 2000; Smith and
Hightower 2012). Because American shad consume minimal prey during freshwater
migrations, energy and weight loss due combined with the release of gametes can be
substantial and lead to spawning mortality (Chittenden 1976; Leggett and Carscadden 1978;
Leonard and McCormick 1999). Northern populations are apparently iteroparous while
southern populations are semelparous, with a transition zone thought to occur in North
passage structures were actually detrimental to the Connecticut River American shad
population as increased migrations may decrease spawning survival, leading to fewer repeat
spawning females and an overall reduction in egg production. However, no known field
studies have thoroughly examined individual weight loss or seasonal spawning survival rates
and potential factors such as sex, temperature, duration, or distance traveled.
Another unknown factor is predation on American shad by introduced species such as flathead catfish *Pylodictis olivaris* and blue catfish *Ictalurus furcatus*. These species have been documented to prey upon young and adult American shad (Ashley and Buff 1987; MacAvoy et al. 2000). However, the potential effect on American shad restoration efforts has received limited evaluation (Pine et al. 2007). Both the extent and timing (e.g., American shad pre- or post-spawning) of predation could have negative influences on adult abundance and annual reproductive success.

Important questions remain in part due to the difficulty of sampling and recapturing American shad. As a highly mobile species present in rivers for a relatively short time period (i.e., typically less than three months), sampling American shad is most effective when fish are congregated at known spawning grounds or downstream of dams. Once captured, American shad can be very sensitive to handling (Hendricks 2003), resulting in mortalities or a “fallback” behavior, where individuals migrate downstream and temporarily or completely abandon spawning migrations (Beasley and Hightower 2000; Bailey et al. 2004; Olney et al. 2006). Telemetry produces valuable data on American shad migration and habitat use, but fallback behavior is common and transmitter battery life and expense limit the duration and number of fish studied (Beasley and Hightower 2000; Bailey et al. 2004; Olney et al. 2006).

I used a resistance board fish weir and passive integrated transponder (PIT) technology that alleviated some of these sampling issues and was successful in capturing, tagging, and tracking thousands of American shad in the Little River, North Carolina in the springs of 2007 through 2010. The consistent fish weir location allowed monitoring of immigration, emigration, and fish conditions (e.g., pre- or post-spawn, weight) relative to
seasonal timing and environmental conditions. Passive integrated transponder tags were relatively inexpensive and lacked batteries (Prentice et al. 1990), allowing me to tag and monitor thousands of American shad and other species over the entire course of the study. However, American shad mortality and fallback were still issues and individuals passed the fish weir uncaptured during high flow events (Raabe, Chapter 2). Installation of PIT antennas increased recapture rates without physical handling, monitored migrations and distributions, and produced individual capture histories used in survival modeling (Castro-Santos et al. 1996; Hewitt et al. 2010). My objectives for this chapter were to examine the demographics of the Little River American shad population, evaluate migrations and distributions relative to environmental conditions, estimate and assess whether weight loss and survival were influenced by distance traveled and other factors, and examine the potential influence of flathead catfish predation on American shad.

METHODS

Study Site

The Little River is a fourth order tributary to the Neuse River, with the confluence near Goldsboro, North Carolina (Figure 3.1). The rivers meet approximately 212 river kilometers (rkm) from Pamlico Sound. Three low head (<4 m in height), run-of-river dams were completely removed from the Little River, another dam was partially removed, and upstream dams still exist (Raabe, Chapter 2). Cherry Hospital Dam (rkm 3.7) was removed in 1998, Rains Mill Dam (rkm 37.7) in 1999, and Lowell Mill Dam (rkm 56.2) in 2005. A partially removed, “notched” dam is present at the City of Goldsboro water treatment plant.
(rmk 7.9) while Atkinson Mill Dam (rmk 82.3) is the furthest intact downstream dam. Collier and Odom (1989) noted American shad likely were able to pass the Cherry Hospital and City of Goldsboro dam during high flow events, but considered Rains Mill Dam impassible. No American shad population estimates exist for the Little River prior to dam removals. Flathead catfish were introduced into the Neuse River approximately 25 years ago (Kwak et al. 2006)

*Fish Sampling and Tagging*

I used a resistance board fish weir to monitor migrations and capture fish for tagging in the springs (March – May) of 2007 through 2010. The weir was installed at the former Lowell Mill Dam site in 2007 (Figure 3.1). I decided to install the weir further downstream at the former Cherry Hospital Dam site in 2008 through 2010 to encounter and tag immigrating and emigrating fish (Figure 3.1). This location also allowed me to tag and monitor migrations throughout the Little River with an array of upstream PIT antennas. I constructed the resistance board weir according to Stewart (2002), with minor modifications to target American shad and accommodate the conditions in the Little River (Raabe, Chapter 2). I checked upstream and downstream weir live cages each morning, evening, and also throughout the day and early night during periods of increased captures. Captured fish were removed with a dipnet and brought to shore where they were identified to species, examined to identify sex, measured for total length (mm), and when possible weighed (g). I examined sex ratios by year, month, and migratory directions, using all individuals captured at the weir.
In 2007, American shad were tagged near the base of the dorsal fin with individually numbered Hallprint 12/13 mm fine T-bar anchor tags. In 2008 through 2010, American shad and flathead catfish received a Texas Instruments PIT transponder (RI-TRP-RE2B). The small (3.9 mm x 31.2 mm, 0.8 g) PIT tags were inserted into the abdominal cavity via a minor incision between the pectoral and pelvic fins for American shad and along the ventral midline for flathead catfish; this rapid procedure required no anesthetic. A handheld reader (Allflex Compact Reader RS200) was used to scan all captured fish. I then released fish upstream or downstream, depending on the cage in which they were captured.

I used electrofishing to supplement weir captures in 2007 and 2009. A Georator with a portable boom supplied 230V DC for electrofishing from a small jon boat to capture and T-bar tag American shad in 2007; all sampling occurred upstream of the fish weir. In 2009 I used electrofishing to PIT-tag American shad during periods of weir failure. I used the Georator unit in middle to lower reaches and conventional electrofishing boats (Smith Root boat units with pulsed DC current (60 Hz) at 3.0–4.0 amps) in downstream reaches near the fish weir and river mouth.

Passive Integrated Transponder Antennas

I installed PIT antennas from 2008 to 2010 to passively monitor fish migrations in the Little River (Figure 3.1). The antennas were comprised of a Texas Instruments Series 2000 reader, Oregon RFID datalogger, two 12 V batteries connected in parallel to power the system, a Texas Instruments tuner box (RI-ACC-008), and a loop of eight gauge audio cable
(Raabe, Chapter 2). I visited antennas every two to four days to exchange batteries, assure proper tuning, and download data.

Three PIT antennas were installed in 2008 and four additional antennas were installed in 2009 and 2010 on the Little River. In all three years, as tagged fish migrated upstream from the weir site, the first antenna was located 190 m downstream of the notched dam at the Goldsboro water treatment plant (rkm 7.7) and a second antenna was installed across the notched dam to monitor fish passage beyond this obstruction (rkm 7.9). In 2008 and 2009, an antenna was installed adjacent to a North Carolina Forest Service facility (rkm 13.4) and upstream of the Rains Mill Dam removal site (rkm 37.7) at Rains Crossroads Road (State Road 2320, rkm 45.3). Another antenna was installed 169 m upstream of the former Lowell Mill Dam (rkm 56.4) in all three years. The final two antennas in 2008 and 2010 were located at Shoeheel Road (State Road 2127, rkm 72.0) and Old Dam Road (State Road 2123, rkm 77.0) to examine upstream habitat use. Upon weir removal, an upstream antenna was relocated to the weir site (rkm 3.7) to monitor emigrants.

Physical Variables

Onset HOBO-TEMP loggers recorded water temperature (°C) at 1.5-h intervals during the sampling period at the weir sites. Water gage height data were obtained for United States Geological Survey (USGS) monitoring station (0208863200) located at Highway 581, immediately downstream of the 2008-2010 weir site (rkm 3.7). A second USGS monitoring station (02088500), located upstream (rkm 45.3) near Princeton, provided water discharge and gage height data.
Migrations

The 2007 upstream weir location provided information on within river migrations, while the close weir proximity to the Neuse River in 2008 through 2010 provided information on immigration (upstream captures) and emigration (downstream captures) events. For migrations throughout the river, I focused on 2009 and 2010 when all antennas were installed for at least half the spawning season. I determined the maximum extent of migrations as the uppermost antenna reached and calculated the total distance traveled (rkm) as the sum of the distance between locations for all upstream and downstream migrations. An upstream or downstream migration occurred when a fish was detected at a new location; repetitive, sequential detections at one antenna were not included. I first examined all detected individuals, and then focused on individuals detected upstream of the notched dam (> rkm 13.4) to account for potential handling and tagging stress, mortality or tag loss. Using Tukey-Kramer HSD tests, I compared potential differences in initial (not recapture) length and weight (by sex) for individuals grouped into the maximum extent they reached (e.g., rkm 13.4, 45.3, etc.). To examine the extent (distance) of weekly migrations, I determined the range (rkm) in locations for all individuals observed at least twice (e.g., capture, detections). I compared the mean weekly extent of migrations to mean weekly flow conditions.

Transition Rates

I calculated minimum American shad transition rates (rkm/h) between locations to examine migratory behaviors. I calculated rates in 2009 and 2010 as the difference in distance (rkm) between sampling locations (weir, antenna) divided by the time (h) between
the last record at a location and the first detection at the subsequent location. Transition rates
would be analogous to swimming speeds when individuals migrated continuously. However,
American shad did not always migrate continuously, likely due to long distances between
sampling locations and potential behaviors (e.g., spawning, resting, delay at obstructions).
I examined potential differences in transition rates by migratory direction, year, and sex
using Wilcoxon rank sum tests. I also used linear regression to examine transition rates
relative to individual total length (mm) and the mean gage height (m) and flow (m$^3$/s)(and
log transformations) between capture/detection events. I compared differences in transition
rates by migratory direction and flow conditions using ANCOVA. Unless noted, all
computations were in program JMP, Pro 9.0 (SAS Institute Inc. 2010).

Diel Activity

I examined American shad diel activity in 2009 and 2010 relative to gear, year, sex,
reaches, migratory direction, and flow. To limit redundancy, I used only the first detection
within a 30-minute period for an individual fish. I rounded capture and detection times to the
nearest hour (e.g., 10:20=10:00, 10:40=11:00) and created histograms with 1-hour bins. I
compared the fish weir to antennas, but for other comparisons I only used antenna data due to
continuous monitoring whereas the weir was influenced by the time of visit and daily effort.
For river reaches, I grouped each detection into lower (rmk 7.7, 7.9, 13.4), middle (rmk 45.3,
56.4), and upper (rmk 72.0, 77.0) reaches. An individual upstream migratory event was the
first detection at an antenna when previously recorded at a downstream location and the last
detection at an antenna when subsequently recorded at an upstream location; downstream
migratory events were determined in the reversed manner. I considered “hold” migratory events to be repetitive detections at the same location excluding upstream or downstream migrations; an individual may have migrated an unknown distance upstream or downstream without being captured or detected. For flow, I assigned each record to a quartile (m$^3$/s) calculated from the Princeton gage for March through May of 2000 through 2010. I visually examined histograms for general patterns because Wilcoxon and Kolmogorov-Smirnov tests were sensitive (routinely produced significant differences) due to large sample sizes and the number of bins.

Weight Loss

I estimated weight loss of recaptured individuals and as groups (immigrating compared to emigrating), in both cases separated by sex. For tagged individuals recaptured at least two days after release at the fish weir, I computed the weight loss (g) between capture and recapture events and the proportion of weight lost (weight difference / capture weight). Using linear regression, I compared both metrics with time upstream, cumulative thermal days (sum of mean temperature for each day upstream), cumulative distance traveled, and the total length and weight at initial capture. Due to low sample sizes, I combined 2009 and 2010. In a separate analysis, I pooled 2008 through 2010 individuals into immigrating and emigrating groups and excluded recaptures. I examined potential differences in immigrating compared to emigrating lengths and weights by month and year using Tukey-Kramer HSD tests for multiple comparisons. I examined relationships between length and weight for the upstream and downstream groups with linear regression and ANCOVA to evaluate potential
differences between migratory directions. Using the linear regression equations, I estimated immigration and emigration weight at 5-mm length intervals (minimum to maximum total lengths for each sex) and estimated proportional weight loss for each interval. From both analyses, I examined the proportional weight loss estimates for apparent survival to emigration thresholds (i.e., proportional weight loss value at which few or no emigrating individuals were captured).

Survival

I estimated American shad spawning season survival using three methods. For the weir-only method I only used weir captures and estimated seasonal survival as

\[
\text{recaptured emigrating individuals} / \text{immigrating tagged individuals}
\]

where only tagged individuals that remained upstream of the weir for at least 24 hours were included. Individuals recaptured within 24 hours were considered “fallbacks” influenced by handling and tagging stresses and excluded. I calculated this estimate for 2007-2010 and used only fish tagged in that year (i.e., excluded returning fish tagged in a prior year because this did not occur in 2007 and 2008). In the weir and antennas method, I accounted for potential tagging stresses, mortality, and tag losses by only using individuals detected at the rkm 13.4 antenna or upstream, and estimated seasonal survival as

\[
\text{emigrating tagged individuals} / \text{tagged individuals detected at } \geq \text{rkm 13.4}
\]

where emigrating tagged individuals included weir recaptures and individuals with distinct emigration patterns at antennas during non-functioning weir periods to include fish that successfully emigrated but were missed at the fish weir. I calculated this estimate for 2009
and 2010 and included returning individuals (tagged in prior year) if they were detected at least twice at rkm 13.4 or upstream antennas. For the third method, I used a state-space Cormack-Jolly-Seber model that estimated weekly survival rates and provided a seasonal estimate by extending the weekly estimate to 12 weeks (i.e., weekly estimate^12). I used the same individuals as in the weir and antenna method. Individual encounter histories depicted whether an individual was captured / detected (1) or not (0) within twelve weekly periods (March 12 – June 3 2009, March 10 – June 1 2010). I used a staggered entry design where individuals were first included in their week of entry (first capture or detection). I also censored emigrating individuals after their last week in the river. Encounter histories were conditional on whether an individual was estimated to be in an alive state (z=1) or not alive / not in the river (z=0; Royle 2008). I fit the CJS models using a Bayesian framework for analysis. I used the open-source software programs JAGS (Plummer 2003; Plummer 2012) and R (R Development Core Team 2012) via the R package “rjags”. I ran three chains with an adaptive phase of 10,000 iterations and evaluated output from an additional 20,000 iterations.

I examined potential factors influencing survival using descriptive statistics, logistic regression, and contingency tests. I calculated the time at large (difference between first and last observations) and the distribution for the last location known river location of all detected individuals. For individuals detected at rkm 13.4 or above, I used logistic regression and contingency tests to examine potential relationships between documented survival (0=recaptured/emigrated) and apparent mortality (1) with day and week of entry, time at
large, maximum upstream extent, total distance traveled, and cumulative flow and thermal
days (sum of daily mean for each day at large).

To determine if American shad returned to spawn in subsequent years and examine
annual survival rates, I scanned all fish captured in the Little River for PIT tags in 2009
for PIT tags in all American shad captured in the Neuse River in 2009 and 2010.

Abundance

I considered the minimum annual American shad abundance as the number of
individuals sampled and also estimated a total number to account for individuals missed at
the weir. In addition to fish captured as the weir, I included electrofishing sampling in 2007
and 2009 and returning individuals that were recaptured or detected in 2009 and 2010.
Individuals that migrated upstream past the weir during failure periods were accounted for
when captured emigrating, but were unsampled if they died upstream or emigrated during
weir failures. I estimated the annual abundance as

\[
\text{sampled} + \text{returning} + \text{emigrating non-recaptures} / \text{survival estimate}
\]

where sampled was the number of individuals captured, excluding recaptures, returning was
returning individuals that were recaptured or detected, and survival estimate was the weir-
only annual apparent survival estimate.

I compared the annual sampled and estimated American shad run sizes within the
Little River to two guideline estimates for healthy populations. These guidelines are
estimated from the amount of available mainstem river habitat and commonly used for
carrying capacity estimates during dam relicensing procedures and to set restoration goals. The most widely used rule-of-thumb of 124 American shad / ha is based on historical data for the Susquehanna and Connecticut rivers (St Pierre 1979). St. Pierre (1979) stated that these projections were estimates of the potential size of a fully restored run in large rivers, but also emphasized that the estimates were only a first approximation based on numerous assumptions. Savoy and Crecco (1994) produced a guideline of 49 American shad / ha from more recent population estimates for the Connecticut River. I used this number as a more conservative estimate of a restored population. To determine the amount of available mainstem Little River habitat, I outlined the bankfull river channel from an aerial photograph layer in ArcGIS 10.0 (ESRI 2010), created polygons for reach (described above), and computed the area (ha). I used PIT antenna distribution rates to estimate the number of American shad that used different river reaches.

*Flathead Catfish Predation*

I estimated the maximum amount of American shad that could be consumed by flathead catfish in the springs of 2009 and 2010. The estimates assumed flathead catfish could consume American shad when their gape width was wider than an American shad’s vertical body depth, they fed in the river at a maximum rate comparable to laboratory study results, and they consumed only American shad that were always present for consumption.

First, I determined flathead catfish sizes (total length) that could consume various sizes (total length; minimum, quartiles, and maximum) of American shad. Size categories were based on the distribution of all American shad collected from 2008 through 2010 at the
Little River fish weir that had both a total length (mm) and weight (g) measurement. I estimated the horizontal gape width (mm) of each flathead catfish from their total length (mm) according to Slaughter and Jacobsen (2008)

\[ gape \, width = 123.9e^{0.0008(\text{total length})} - 119.3 \]

For flathead catfish tagged in 2009 and detected but not recaptured in 2010 (n=37), I increased their total length (mm) based on the growth rate (\( \text{growth} / 2009 \, \text{total length} + 1 \); mean=1.0103) of all returning, recaptured individuals (n=15). I estimated American shad body depth (mm) from total length (mm) based on measurements of preserved specimens (n=11, \( R^2=0.83 \)):

\[ \text{body depth} = 8.4255 + 0.2265(\text{total length}) \]

I estimated flathead catfish maximum daily consumption rate (% body weight (g) / day) based on the daily mean Little River water temperature (°C; n=39, \( R^2=0.61 \)):

\[ \text{daily consumption rate} = -0.6886 + 0.0140(\text{temperature}) + 0.0038(\text{temperature}^2) \]

I developed the equation using data from Bourret et al. (2008) of juvenile flathead catfish maximum daily consumption at different water temperatures, using only the published water temperatures (11-26 °C) near the range experienced in the Little River during the study period (12-25 °C). Flathead catfish were not weighed, so I estimated their weight (g) from total length (mm) using a length-weight curve (n = 79, \( R^2 = 0.94 \)):

\[ (\text{weight} = 0.0000017159(\text{total length}^{3.2968727666}) \]

I developed the curve from flathead catfish data collected in the Neuse and Cape Fear river systems (Pine 2003), using only individuals within the size range (\( \geq 636 \, \text{mm} \)) estimated as capable of consuming American shad observed in the Little River.
I estimated the maximum potential daily and seasonal consumption of American shad by flathead catfish in five size categories (minimum, quartiles, maximum) for 2009 and 2010. For example, the “minimum” size category included all catfish large enough to consume only the smallest American shad while the “maximum” category included only individuals capable of consuming all sizes of American shad. The estimated weight (g) of an individual flathead catfish was included in the daily cumulative flathead catfish biomass (g) starting on its day of entry (first capture or detection) through the end of the study period (June 1); no tagged flathead catfish were recaptured or detected emigrating during this period. I did not include “fallback” (recaptured migrating downstream within 24 hours) individuals unless they were later recaptured or detected upstream; in these cases the return date was their day of entry. For each day, I multiplied the cumulative flathead catfish biomass by the daily ration (% body weight at daily mean water temperature) to estimate the consumed biomass (g). To estimate the number of American shad consumed, I divided the estimated cumulative biomass consumed by 716 g, the median weight from 2008 through 2010.

Some flathead catfish PIT-tagged in 2009 were missed at the weir in 2010 but detected at antennas. Therefore, I expanded the total number of 2010 flathead catfish by estimating the number of untagged individuals that migrated past the weir as:

\[ \text{2009 only detected returning} \times \text{untagged 2010 captures} / \text{2009 recaptured returning} \]

For American shad consumption estimates, I assumed estimated flathead catfish had the same size and temporal distribution as sampled flathead catfish, and thus spring consumption rates (estimated biomass consumed / individual). For each size category, I multiplied the appropriate seasonal rate by the estimated number of flathead catfish.
RESULTS

Demographics

A total of 5,085 American shad captures occurred at the weir from 2007 through 2010 (Table 3.1). The fewest American shad were captured in 2007 when the weir was installed upstream (rkm 56.4) while the most American shad were captured in 2009 despite the weir functioning for the fewest days. Except for 2010, substantially more individuals were captured migrating downstream.

The annual female to male sex ratio ranged from 0.71 in 2010 to 1.41 in 2009 (Table 3.2). In all four years, males were more common in both upstream and downstream March captures and were generally more common in all 2007 captures when the weir was located upstream (Table 3.2, Figures 3.2 and 3.3). Females were consistently more abundant in April downstream catches in all four years, and were generally more common in April and May of 2009 and 2010 (Table 3.2, Figures 3.2 and 3.3).

Migrations

American shad were captured migrating upstream at the weir from March through May, with increased captures during high flow periods (Figures 3.2 and 3.3). The coolest temperature when an American shad was captured at was 9.6 °C on March 16, 2009. However, American shad were always captured upon weir installation, indicating individuals had immigrated prior to weir installation in cooler water. The warmest water temperature for an immigrating American shad capture was 24.1 °C on May 15, 2010. Distinct upstream migrations occurred during freshets prior to weir failures in late March to early April in 2008,
early May 2009, and both mid-March and the end of March in 2010. Males dominated the immigration events in 2008 and 2010 but females dominated the 2009 event. Few or no individuals were captured migrating upstream during low flows.

Downstream American shad captures were also influenced by flow conditions, but water temperatures appeared to play a larger role compared to upstream captures (Figures 2.2, 2.3). A large downstream migration event (300 individuals over seven days) of males and females occurred during low flows in 2007 when water temperatures rose to 22.8 °C. In 2008, 314 American shad emigrated on April 28 and 29 (31% of all captured emigrating individuals) when the mean daily flow rose from 2.9 m$^3$/s on April 27 to 32.9 m$^3$/s on May 1 (weir inundated on April 30). Male and female American shad began emigrating in higher numbers starting with a smaller freshet on April 21 when mean daily water temperatures exceeded 18 °C and reached 21.5 °C on April 27. The emigration period in 2009 was even more profound, as 905 American shad emigrated from May 6 through 8 (57% of all captured emigrating individuals), as mean daily flow rose from 1.6 m$^3$/s on May 5 to 11.0 m$^3$/s on May 9 (weir inundated on May 9). Females outnumbered males on May 8, the largest emigration day. Mean daily water temperatures had exceeded 20 °C, starting on April 25. Only 387 American shad were captured emigrating in 2010, and no distinct emigration events occurred. A total of 148 individuals were captured emigrating from April 8 through May 5 when flows were low and mean daily water temperatures ranged from 17.0 to 23.7 °C. Only a small increase in emigrating individuals occurred during a freshet starting on May 18 when water temperatures were above 19 °C and even fewer individuals emigrated during additional freshets in late May.
Male and female American shad migrated into the upper extent of restored habitat in the Little River, but many migrations concluded in downstream and middle reaches in both 2009 and 2010 (Figure 3.4). Over 0.4 of all detected female migrations were limited to between rkm 7.7 and 13.4 in both years whereas slightly over 0.2 males migrations ended in this reach; the Goldsboro notched dam is located at rkm 7.9. Similarly, a large proportion of individuals, including slightly more males than females, ended migrations in the long reach between rkm 13.4 and 45.3. The proportion of individuals concluding migrations in different middle to upper reaches was more uniform, with a higher proportion of males accessing the uppermost reach downstream of Atkinson Mill Dam (rkm 82.3). No significant differences (p >0.05) were detected between reaches for the total length or weight of females in 2009 and males in 2009 and 2010. Female weight was significantly higher (p=0.015) in the uppermost reach (rkm 72.0-82.3, mean=1456.3 g, SE=62.22) compared to the lower to middle reach (rkm 13.4-45.3, mean=1220.2 g, SE=35.10) in 2010, but no other significant differences were detected for females in 2010.

Date of entry combined with river flow conditions influenced the extent of American shad migrations. Many individuals tagged or returning early in 2009 migrated into upper reaches, primarily during large March freshets (Figure 3.5); downstream antennas were not installed or functioning until April 2009. Individuals tagged during decreasing flows in the April and early May 2009 displayed a mixture of remaining downstream and migrating upstream during May smaller freshets. In 2010, a considerable number of American shad tagged in March migrated past rkm 45.3 (Figure 3.5). Individuals tagged during low flow conditions in April 2010 primarily remained in downstream reaches, with a few migrating
further upstream during May freshets. Late immigrating individuals also migrated upstream, as indicated by individuals tagged during freshets in mid to late May 2010. The mean range in weekly individual locations displayed a positive relationship between the extent of migrations and river flows conditions (gage height) in both years (Figure 3.6). The weekly movement rate could not be calculated in the first half of 2009, but increased notably during a May freshet. In 2010, the rate closely tracked the trend in mean gage height.

*Transition Rates*

American shad transition rates ranged from <0.01 to 5.50 rkm/hr in 2009 and 2010, with an overall mean of 0.49 rkm/hr (SE=0.016, n=1834). Due to missed detections at antennas, the difference in distance between detections used in calculations ranged from 0.2 to 73.3 rkm; rates were less variable for long distance (e.g., <2.1 rkm/hr for distances >40 rkm) calculations, with a weak, positive relationship (p<0.0001, R²=0.009) between distance between records and transition rates. Transition rates were significantly higher (p<0.0001) for individuals migrating downstream compared to upstream in both years. Downstream migrations reached 5.50 rkm/hr (mean=0.95, SE=0.068, n=295) while the fastest upstream migration was 3.15 rkm/hr (mean=0.41, SE=0.013, n=1,539). Compared to 2009, American shad transition rates in 2010 were faster during downstream migrations (p = 0.02) but comparable for upstream migrations (p=0.35). Males tended to transition faster than females in the downstream direction (p=0.055) but were similar swimming in the upstream direction (p=0.51). A positive relationship existed between transition rates and flow conditions (i.e., gage height, discharge) in both years for both directions. Rates were more variable at higher
flow conditions and in the downstream direction. For both years combined, downstream transition rates displayed a significantly steeper slope \( (p<0.0001) \) with log discharge than upstream migrations, although the model explained only 23% of the variation (Figure 3.7). A very weak, positive relationship \( (p=0.051, R^2=0.01) \) existed with transition rates and associated individual total lengths in the downstream direction but no relationship existed with total lengths and upstream migrations \( (p=0.744, R^2<0.01) \) for both years combined.

American shad transition rates were generally faster in middle and upstream reaches in 2009 and 2010 and individuals could sustain rapid transition rates over long distances, especially during freshets. Individuals migrating upstream from the weir (rm 3.7) to the first antenna (rm 7.7) were generally slow \( (\text{mean}=0.11 \text{ rkm/h}, \text{SE}=0.007, n=510) \) but downstream rates in this reach were not much faster \( (\text{mean}=0.27 \text{ rkm/hr}, \text{SE}=0.060, n=32) \). Individuals migrating from rm 45.3 to 56.4 had a mean transition rate of 0.44 rkm/h \( (\text{SE}=0.045, n=78) \) compared to a mean of 1.14 rkm/h \( (\text{SE}=0.263, n=35) \) in the downstream direction. Upstream and downstream transition rates were comparable between rm 72.0 and 77.0 at means of 1.04 rkm/h \( (\text{SE}=0.094, n=76) \) and 1.06 rkm/h \( (\text{SE}=0.183, n=28) \). For individuals detected at rm 7.7 and 77.0 in 2010, the upstream transitions ranged from 2.89 to 59.5 days \( (\text{mean}=12.54, \text{SE}=1.616, n=50) \), relating to transition rates of 1.00 to 0.05 rkm/hr. In comparison, downstream migrations from rm 77 to 7.7 were between 1.00 and 11.27 days \( (\text{mean}=4.39, \text{SE}=1.71, n=6) \), or 2.89 and 0.26 rkm/hr. Certain individuals migrated into the upstream reach rapidly during freshets, while others appeared to migrate slowly during lower flows until a freshet occurred (Figure 3.8).
Diel Activity

American shad displayed similar diel patterns between gears and at antennas for year and sex (Figure 3.9). American shad weir captures and antenna detections followed a comparable trend throughout the day with a peak at 20:00, however antennas detected individuals between 2:00 and 7:00 while no fish were captured at the weir. American shad weir captures steadily increased from 14:00 to 20:00, dropping off sharply at 21:00. This decline was not simply due to sampling effort as the weir was routinely checked at night (21:00 and 0:00) and captures in the initial morning sampling were not noticeably higher. In both 2009 and 2010, diel activity at antenna locations peaked at 20:00-21:00, was higher at 0:00, and displayed a smaller mode at 6:00-7:00. Daytime antenna activity (7:00-15:00) was generally higher in 2009, while American shad were slightly more active between 1:00 and 5:00 in 2010. For both years combined at antennas, male and female patterns were very similar, with males displaying a mode at 0:00 and slightly more active between 15:00 and 19:00 while females were generally more active between 5:00 and 14:00.

American shad diel patterns at antennas differed between migratory directions, river reaches, and flow quartiles; trends were consistent between 2009 and 2010. Upstream migratory events steadily increased from 5:00 to 16:00, then decreased after 18:00 (Figure 3.10). Hold events depicted high early nocturnal activity (20:00-1:00) and smaller crepuscular peaks at 6:00 (Figure 3.10). Downstream migratory events were more common during daylight, with two smaller peaks at 9:00 and 14:00 (Figure 3.10). Diel activity in the lower reach displayed a similar pattern to the overall diel activity because the majority of records occurred in these locations (Figure 3.11). In the middle reach, American shad
activity was more uniform with the highest peak at 6:00 (Figure 3.11). Diel activity was also more uniform in the upstream reach, although individuals were more active during daylight hours than in the other two reaches (Figure 3.11). During the lowest flow conditions, American shad displayed minimal activity in the morning (7:00-12:00), instead moving between 20:00 and 0:00 (Figure 3.12). In the middle flow quartiles, activity picked up slightly during the day including early morning (6:00-7:00) modes, although overall activity was still highest in the evening and early night (Figure 3.12). However, in the highest flows American shad diel activity shifted noticeably to daylight hours, with much fewer records between 20:00 and 5:00 (Figure 3.12).

**Weight Loss**

Female American shad ranged from 385 to 575 mm in total length (mean=481.5, SE=0.67, n=1328) whereas males ranged from 346 to 515 mm (mean=425.5, SE=0.70, n=1343). Weight for upstream captures ranged from 446 to 1956 g for females (mean=486.9, SE=0.97, n=582) and from 350 to 1265 g for males (mean=763.4, SE=6.28, n=734). A few significant differences occurred between years (2008-2010) for length and weight based on migratory direction for both sexes, but could be a result of when the majority of American shad were captured each year (Figures 3.2 and 3.3) as individuals tended to be larger earlier in the season when combining the three years (Table 3.3). In particular, mean weight for upstream captures significantly decreased from March through May for both sexes. Individuals of both sexes were longer in total length in March but
similar in April and May for upstream captures. Similar patterns existed for downstream migrating American shad, although very few individuals were sampled in March.

For recaptured individuals in 2009 and 2010, male weight lost ranged from 12 to 264 g (mean=88.9 g, SE=15.11, n=23) while females lost between -3 and 984 g (mean=307.7 g, SE=37.56, n=52). The proportion of weight lost ranged from 0.01 to 0.33 (mean=0.12, SE=0.020) for males compared 0 to 0.64 (mean=0.24, SE=0.25) for females (Figure 3.13). Visually, most males captured migrating downstream did not exhibit obvious weight loss and appeared healthy, while some females were extremely emaciated (Figure A.8) and acted lethargic with minimal opercular and caudal fin movement. In linear regression analyses, proportion of weight loss appeared to be a better response variable (higher R²) than total weight loss. For both sexes, proportion of weight loss displayed a strong, positive response to cumulative thermal days and time upstream, and a weaker positive response to cumulative distance traveled (Figure 3.13). However, no relationships existed with the capture total length or weight (Figure 3.13), even when including thermal days or time upstream in multiple regression analyses.

When pooling non-recaptured American shad, downstream captures weighed significantly less than upstream captures for both males (mean upstream=763.4 g, SE=5.59; mean downstream=572.5, SE=6.13; p<0.0001) and females (mean upstream=1240.4 g, SE=8.75; mean downstream=696.8, SE=7.74; p<0.0001). In addition, upstream and downstream slopes were significantly different (p<0.0001) for both sexes, with downstream slopes more gradual than upstream slopes indicating proportionally greater weight loss for large individuals (Figure 3.14). Using respective regression equations, estimated
proportional weight loss ranged from 0.09 (345 mm) to 0.26 (515 mm) for males (mean=0.21, SE=0.008) and 0.38 (575 mm) to 0.48 (385 mm) for females (mean=0.41, SE=0.003).

Survival

All three methods estimated a low spawning season survival rate for American shad in the Little River (Table 3.4). All estimates are considered a minimum, or apparent survival rate because individuals were able to emigrate uncaptured during weir failure periods. In the weir only method, survival was highest in 2007 but it is unknown if individuals survived from this upstream weir location to the downstream weir location. When considering only individuals detected at rkm 13.4 or upstream and accounting for individuals that were clearly missed at the weir, estimated survival rates decreased slightly in both 2009 and 2010. Weekly CJS survival estimates also depicted higher survival in 2009 (mean=0.847, 95% credible intervals=0.7972-0.8946) than in 2010 (mean=0.814, 95% credible intervals=0.7911-0.8363) but within the margins of uncertainty. The CJS survival estimates were comparable to the other seasonal estimates when extended to 12 weeks residence in the river.

American shad tagged in previous years returned to the Little River, but at very low numbers. Eight of 699 individuals tagged in 2008 returned in 2009 and six of 1277 tagged in 2009 returned in 2010. Within season survival was considerably higher for the eight returning fish in 2009 (0.625) but none of the six returning individuals in 2010 were documented emigrating. One returning American shad was captured at the weir in 2010 but never detected at antennas while one 2009 and two 2010 returning individuals were not
captured but detected only once. No American shad scanned in the Neuse River contained a Little River PIT tag in 2009 (n=293) or 2010 (n=365).

Many American shad appeared to die in their maximum upstream reach as they did not initiate a downstream migration in 2009 and 2010, but those that did typically migrated near or past the weir site regardless of their extent of upstream migration (Table 3.5). A large proportion of males and females apparently died between rkm 7.7 and 45.3 and downstream initiation rates were also low between rkm 45.3 and 56.4 in 2010. In 2009, 21% of detected females initiated a downstream migration and all reached at least the rkm 7.7 antenna or were recaptured. A total of 24% of detected males initiated migrations in 2009 and only two migrating from rkm 77.0 in 2009 did not reach rkm 7.7 or the weir, with one last detected between rkm 56.4 and 72.0 and the other between rkm 45.3 and 56.4. In 2010, 16% of females initiated a downstream migration with 13% migrating into the most downstream reach. A similar percentage (15%) of males initiated migrations in 2010, including relatively higher proportions in upstream reaches, but only 8% appeared to complete migrations downstream. On May 13, 2010, I recovered a dead male American shad in vegetation along the bank immediately downstream of Atkinson Mill (rmk 82.3; Figure A.9). This individual (164509898), tagged at the weir on March 15, 2010 (430 mm, 843 g), was last detected migrating upstream at rkm 77.0 on March 20, 2010.

American shad displayed no clear distinctions between individuals that survived to emigrate from the Little River and those that apparently died upstream. For individuals detected at rkm 13.4 or upstream in 2009 and 2010, a similar proportion of tagged males (0.09) and females (0.10) successfully emigrated. A contingency analysis showed no
relationship (Pearson=0.99) between survival and maximum extent reached, as survival rates ranged from 0.09 at rkm 77.0 to 0.11 at rkm 44.0. Survival and total distance traveled displayed a significant (p<0.0001), positive but weak relationship, likely due to the large number of individuals only traveling 13.4 rkm and apparently dying compared to the few individuals successfully emigrating from upstream reaches. Survival rates varied by week of entry (p=0.043), ranging from 0.0 in weeks 5 and 10 to 0.67 in week 4, but the contingency analysis results are suspect due to low sample sizes in certain weeks and logistic regression showed no relationship with date of entry. Time at large displayed a weak but significant (p <0.0001), positive logistic relationship with surviving individuals, ranging from 1.8 to 74.9 days for emigrating individuals (mean=33.0, SE=3.17, n=41) and 0.1 to 88.3 days (mean=18.0, SE=0.87, n=399) for remaining individuals. Other cumulative metrics (e.g., sum of discharge, temperature) showed similar, positive but weak relationships with survival.

**Abundance**

The number of sampled and estimated American shad increased from 2007 through 2009, but estimated abundance decreased in 2010 (Table 3.6). Electrofishing slightly supplemented weir captures in 2007 (23) and 2009 (17). In both 2009 and 2010, five returning individuals only detected at antennas were added to the total number sampled. The fewest American shad were sampled in 2007, however when accounting for the upstream weir location (divided total sampled by proportion (0.31) that migrated to rkm 56.4 or upstream in 2010) the estimate was higher than the number sampled in 2010. The estimated total number (sampled plus estimated unsampled) of American shad was substantially higher
than sampled individuals in 2007 through 2009. Estimated abundance exceeded the 49/ha guideline in 2008 and 2009 but was still at least 50% lower than the 124/ha rule-of-thumb. The 2010 estimated abundance was noticeably lower than other years, largely due to few downstream captures.

Assuming unsampled American shad followed a similar spatial distribution (maximum extent) as tagged individuals, estimated American shad concentrations were highest downstream of rkm 45.3 (Table 3.7). The large reach (77.8 ha, 0.47 of total area) between antennas at rkm 13.4 and 45.3 contained the most American shad. However, the smaller (12.0) reach from downstream of the Goldsboro notched dam (rmk 7.7) to rkm 13.4 had a disproportionally higher concentration (0.28 - 0.35) compared to guideline estimates (0.07). Similarly, the small (10.1 ha) reach leading up to Atkinson Mill Dam (rmk 82.3) contained a disproportionally higher number of American shad, especially in 2010.

Flathead Catfish Predation

I documented at least four cases of flathead catfish consumption of American shad in the Little River. On May 8, 2009, I noticed an American shad caudal fin protruding from the gullet of a 962 mm flathead catfish captured in the upstream weir cage. On May 12, 2009, a 740 mm flathead catfish (estimated gape width = 104.7 mm) was found dead on the weir panels (downstream direction). Its stomach contained minimal organic material but the PIT tag of a 452 mm male American shad (estimated body depth = 110.8 mm) tagged migrating upstream on May 1, 2009 remained. In 2010, two large flathead catfish captured in the upstream cage contained PIT tags from American shad released upstream at the weir that
likely migrated downstream when the weir was not functioning properly. In these cases, a 396 mm male (tagged on 5/21/10, estimated body depth = 98.1 mm) and a 441 mm male (tagged on 5/19/10, estimated body depth = 108.3 mm) American shad were consumed by a 922 mm (captured on 5/27/10, estimated gape width = 139.8 mm) and a 980 mm (captured on 5/29/10, estimated gape width = 152.1 mm) flathead catfish. Because emigrating American shad did not appear to return later to the Little River post-spawning, it is possible three spent female (434-457 mm) and one male (420 mm) PIT-tagged American shad released downstream between May 14 and 21, 2009 were consumed by flathead catfish as these PIT tags were detected at an antenna (rkm 3.7 or 7.7) between June 11 and 13, 2009. Based on estimated American shad body depths and flathead catfish gape widths, a flathead catfish 636 mm or larger in total length could potentially consume a 346 mm American shad, the minimum total length captured from 2008-2010 (Table 3.8). From March 10 through June 1, total flathead captures were one in 2008, 72 in 2009 and 199 captured or detected in 2010. However, 22% of flathead catfish were too small (490-634 mm) to consume American shad in 2009 while 27% were too small (419-633 mm) in 2010. There were noticeable reductions in the number of flathead catfish capable of consuming American shad throughout the bottom quartile (25%) of total length compared to those capable of consuming only the minimum American shad size, especially in 2010 (Table 3.8, Figure 3.15). However, in both years minimal reduction in flathead catfish capable of consuming American shad in the 25% through 75% quartiles occurred, and 34-37% of the flathead catfish capable of consuming American shad could consume all lengths (Table 3.8, Figure 3.15). In 2009 consumption analyses, I excluded the dead flathead catfish (added one
American shad to totals) and four sufficiently sized flathead catfish that immediately migrated downstream and did not return during the study period.

Flathead catfish size, date of entry, and water temperatures influenced the total estimated consumption of American shad (Figure 3.16). In March, only one flathead catfish (659 mm) was captured in 2009, in part due to weir failures, while the majority entering in 2010 were either too small or could only prey on the smallest American shad. Flathead catfish were estimated to commence feeding around 12 °C and the daily consumption rate was under 0.5% of body weight until 16 °C. Therefore, little consumption occurred in March. Very few flathead catfish, especially larger individuals, were detected or captured in April 2010 (none in April 2009), but rising water temperatures resulted in an increase in estimated predation numbers (e.g., mean water temperature=18.6 °C, 0.9% body weight/day) for those in the river. In May of both years, increases in the number of flathead catfish (especially during freshets), the size of immigrating individuals, and water temperatures occurred, producing sharp increases in the estimated number of American shad consumed. Estimated daily flathead catfish consumption rates increased to 1% of their body weight at 19.5 °C and 2% at 25 °C. In total, tagged flathead catfish upstream of the fish weir were estimated to consume between 108 and 193 American shad in 2009 and between 237 and 472 individuals in 2010 (Table 3.8).

I also estimated the total number of individuals in the Little River and their estimated American shad consumption (Table 3.8). Individuals tagged in 2009 returned in 2010, with some recaptured at the weir (15) while others were only detected (34) from March 10 through June 1. Returning individuals that were only detected appeared to enter the Little
River in three different periods: prior to weir installation, during a week when the weir was flooded, and in mid to late May when the weir captured fish (including flathead catfish) but submerged panels allowed fish to pass over the weir. Based on 2009 returning individuals, I estimated 340 flathead catfish passed the weir unsampled (34 detected but not recaptured * 150 untagged / 15 recaptured). This resulted in an estimated 539 total flathead catfish upstream of the weir in 2010 that could consume an estimated 643 to 1,278 American shad.

Flathead catfish and American shad overlap varied spatially and temporally in the Little River (Figure 3.17). In 2009, nearly all captured flathead catfish entered the Little River in May and remained in downstream or middle reaches. Only two individuals, one capable of consuming American shad (713 mm) and the other not (555 mm), were detected at rkm 56.4 but not further upstream. In contrast, American shad were captured in March, April, and May and occupied middle and upstream reaches. In 2010, a few flathead catfish capable of consuming American shad entered the river in March, remaining in downstream or middle reaches (none detected at or upstream of rkm 45.3) while American shad occupied all reaches. American shad continued to enter the river and were detected in all reaches in April while very few flathead catfish entered. Tagged flathead catfish displayed minimal movement (rarely detected) in April, although two capable size (643 and 664 mm) and three smaller (529-574 mm) individuals were detected in middle reaches (rmk 45.3 and 56.4). Spatial overlap was greatest in May when more flathead catfish entered the river and occupied all reaches, including six capable (646-1171 mm) and five smaller (529-629 mm) individuals detected in the uppermost reaches (rmk 72.0 and/or 77.0). Throughout 2010 the greatest overlap occurred at rkm 7.7, immediately downstream of the notched dam (rmk 7.9).
DISCUSSION

*Migratory Behavior*

American shad were present in the Little River from March through May in all four years. While American shad were in the Little River, water temperatures were usually within the 8 °C to 26 °C range reported by Walburg and Nichols (1967) for spawning activity. In 2009 and 2010, non-fallback recaptured individuals were upstream for 1.8 to 74.9 days. Survival duration prior to mortality may vary widely, as tagged individuals that did not appear to complete emigration were detected for 0.1 to 88.3 days; it is unknown how long individuals resided in areas not sampled by antennas. In all years, American shad primarily emigrated after mean daily water temperatures remained above 20 °C, suggesting individuals waited to spawn until the optimal range of 14 to 22 °C was attained (Walburg and Nichols 1967; Hightower et al. 2012).

Male American shad tended to immigrate earlier than females but exhibited similar migratory behaviors and distributions. Previous studies have also noted males being more abundant early in the season until female numbers increased or exceeded males in the middle and later portions (Walburg and Nichols 1967; Chittenden 1975). Little River seasonal female to male sex ratios ranged from 0.76 in 2007 to 1.41 in 2009. Sex ratios were likely confounded by temporal differences in weir efficiency, schooling behaviors, and variability in environmental conditions. When functioning properly, the weir did not appear to have a sex bias and sampled continuously rather than a snapshot provided by traditional gears. For example, in the adjacent Neuse River from 2000 to 2005 males were more common in electrofishing surveys (M:F=1.3-3.2) but females were more common in gill-net surveys.
(M:F=0.1-0.3; ASFMC 2007). Diel activity was nearly identical between males and females, and transition rates were comparable with males transitioning through reaches slightly faster during downstream migrations. Both sexes used the entire extent of habitat restored by dam removals as evident by migrations past an antenna at rkm 77.0. General distribution patterns were similar between sexes, although more females remained downstream (rkm 7.7-13.4) while more males migrated into the uppermost reach (rkm 77.0-82.3) in both 2009 and 2010. These differences may be a result of when males and females entered the river, especially relative to when freshets occurred.

Flow conditions strongly influenced American shad migrations and behavior in the Little River. I (Chapter 2) determined a significant, positive relationship between the daily flow (gage height, discharge) and number of American shad captures and detections in the Little River, with a potential decline at the highest flow conditions. This relationship held for both males and females as immigration and emigration captures increased during freshets. Weaver et al. (2003) also observed a positive trend between annual mean discharge and American shad fishway passage on the James River, Virginia. American shad were captured at the fish weir throughout the day, especially during elevated flow conditions. However, diel activity decreased rapidly after 20:00 at the fish weir. American shad may be hesitant to traverse migratory obstacles during the night, as indicated by low nocturnal fish passage rates (Haro and Kynard 1997; Weaver et al. 2003). Increasing flows likely serve as a migratory cue and may assist individuals migrating in the Neuse River with locating and entering the Little River (Jonsson 1991; Jowett et al. 2005). For example, the most American shad were captured in 2009 when three large freshets occurred in March through early April.
American shad may spawn during upstream migrations and lower flow conditions, but migrate rapidly during increased flows to access different habitats. Upstream transition rates averaged 0.41 rkm/h and were noticeably slower during low flow conditions, potentially due to migratory impediments or spawning activity. American shad were most active between 20:00 and 22:00 during low flow conditions, possibly to decrease predation vulnerability but this is a known time range for spawning activity (Ross et al. 1993; Hightower and Sparks 2003; Smith and Hightower 2012). In contrast, American shad migrated extensively, rapidly, and during daylight hours at the highest flows, suggesting migrations were the primary focus. Elevated flows may aid passage at man-made (e.g., notched dam) and natural (e.g., rock ledges, tree snags) obstructions (Beasley and Hightower 2000; Ovidio and Philippart 2002; Raabe, Chapter 2). Increased turbidity during freshets may provide an opportunity to migrate with limited threat of predation (Jonsson 1991) and access habitat with fewer predators. American shad diel activity was more uniform throughout the day in middle and upstream Little River reaches containing fewer large predators (Raabe, Chapter 2). American shad may also migrate upstream during freshets to access optimal spawning habitat that includes gravel, cobble, boulder, and bedrock substrates, depths between 1.5 and 4.0 m, and velocities above 0.6 m/s (Hightower et al. 2012). Cobble and larger substrates were only present above rkm 13.4 in the Little River (Raabe, Chapter 2). In addition, upstream reaches may provide an optimal combination of food availability and predation risk for American shad fry and juveniles (Limburg 1996). Alternatively, American shad may migrate during freshets when conditions at their current location are no longer ideal for spawning. For example, downstream of the weir during
certain low flow periods I observed individuals milling during the day and spawning splashes in the evening and night in fine gravel and sand areas. When flows subsequently increased, American shad upstream captures increased and spawning splashes were not observed. On average, American shad upstream transition rates were higher in the Roanoke River (mean=0.99 rkm/h; Hightower and Sparks 2003), potentially due to sustained higher flows and concentrated upstream spawning grounds compared to lower flows and available spawning habitat throughout the Little River.

Surviving American shad appeared to emigrate promptly post-spawning. Downstream migrations were less common than upstream migrations but transitions were more rapid (mean=0.95 rkm/h). River current may simply make upstream swimming more physically challenging. However, river current potentially aided American shad, as downstream migrations were also extensive in freshets, including emigrants that traversed the entire river. These observations suggest that American shad, when possible, emigrate rapidly downstream throughout the day post-spawning. This contrasts with Maltais et al. (2010) who stated American shad spawning events progressed in a downstream manner because juveniles in downstream reaches hatched later in the spawning season. However, later arriving individuals may not migrate as far upstream due to no or fewer freshet events or more rapid depletion of energy reserves at higher water temperatures (Leggett 1972).

American shad responses to flow conditions may be elevated in tributaries such as the Little River, but flow is likely an important migratory factor in mainstem rivers as well, including rivers regulated by dams. For example, Burdick and Hightower (2006) collected more American shad eggs in upstream Neuse River habitat during a high flow year compared
to a lower flow year. Crecco et al. (1986) hypothesized that a positive relationship between mean annual May flow and American shad recruitment numbers in the Connecticut River was due to decreased water temperatures delaying spawning until conditions were optimal for hatching young, but it is possible higher flows aided migrations and reproductive success.

**Weight Loss**

Recaptured females lost more weight and a higher proportion of their initial weight than males. Proportional weight loss was positively related to water temperature (cumulative thermal days), duration upstream, and to a lesser extent distance traveled, all likely due to increased metabolic rates (Leggett 1972). For fish captured only immigrating or emigrating, estimated proportional weight loss was again higher for females (0.38 – 0.48) than males (0.09 – 0.26). These estimates are lower than in previous studies using a similar method, in particular for males. Leggett (1972) estimated a mean total weight loss of 0.48-0.55 for males and 0.53 for females (estimated 40-100 days in river) while Chittenden (1976) estimated 0.45 for males and 0.57 for females (estimated ≥ 60 days in river). Leggett (1969) determined full ovaries weighed an average 0.13 of female total weight while Chittenden (1976) found averages of 0.14 for ovaries and 0.07 for testes. Therefore, somatic weight loss appears relatively minimal for males and more considerable for females in the Little River. Visually, downstream migrating males in the Little River often appeared relatively healthy while some spent females were emaciated, lethargic, and barely swimming or died during handling. Other studies have also found deteriorated conditions of American shad following substantial weight loss (Walburg 1960; Leggett 1972; Chittenden 1976). Interestingly, size
(especially weight) decreased in each month (March–May) for both sexes and in both directions. This may indicate larger individuals immigrate and emigrate earlier in the season, but is more likely a function of increased energy expenditure and weight loss at warmer water temperatures (Leggett 1972).

Survival

American shad spawning mortality appears to be substantial in the Little River and may explain why North Carolina populations are primarily semelparous (Leggett and Carscadden 1978). Apparent survival ranged from a low of 0.084 in 2010 to 0.238 in 2007 using only weir data; rates incorporating antenna data in 2009 and 2010 were comparable. However, the 2007 estimate was for survival above rkm 56.4 (weir location) and individuals may not have migrated past the downstream weir location (rmk 3.7) used in other years. No previous studies have estimated seasonal survival. However, in Neuse River assessments using catch curves, annual survival ranged from 0.07 to 1.00 for males and 0.09 to 0.86 for females when using estimated age compared to 0.01 to 0.32 for males and 0.02 to 0.42 for females when using repeat spawn marks on scales (ASMFC 2007). While estimates were highly variable and American shad scales can have considerable inaccuracies (McBride et al. 2005), seasonal spawning survival may be the main component in annual survival for North Carolina populations.

Factors attributing to survival were not apparent in the Little River, but survival may be influenced by flow conditions. Large emigration events occurred in late April to early May in 2008 and 2009 during freshets. It is likely that increased flows aided downstream
emigrations of physically exhausted American shad (Jonsson 1991), and in turn their survival to emigration. No large emigration event occurred in 2010, the year with the lowest estimated survival and no freshets until mid to late May. More females were captured emigrating, but tagged individuals depicted a similar survival rate between sexes. American shad survival rates tended to be higher when individuals entered the Little River during weeks of higher flow (or if flow increased shortly after entry). During low flow periods, shallower, clearer water, narrower channels, and migratory impediment (e.g., Goldsboro notched dam) may increase American shad vulnerability to predation. Individuals may have succumbed to spawning mortality during low flow periods (e.g., weeks 6-10 in 2010) when energetically exhausted individuals were “trapped” at man-made and natural migratory impediments as water temperatures rose. Harris and Hightower (2011) detected transported tagged American shad remaining in Roanoke River reservoirs, often just upstream of a dam, late in the spawning season and ultimately dying. In a Connecticut River simulation model, Castro-Santos and Letcher (2010) determined delays at dams, especially in the downstream direction, had a stronger influence on American shad survival to the ocean than their distance traveled. While Leggett et al. (2004) suggested increased American shad migrations following fish passage and dam removal efforts may lead to higher spawning mortality, I observed no direct relationships between survival and distance traveled upstream.

Based on both recaptures and estimated numbers, an apparent survival threshold of 0.5 proportional weight loss existed for females and 0.3 for males to emigrate from the Little River. A female with 0.64 proportional weight loss migrated downstream to the weir but was extremely gaunt and found dead on the weir panels. Changes in American shad tissue weight
were found to be a reliable index for the extent of energy used during migrations (Glebe and Leggett 1981); my estimates included gonadal and somatic weight loss. Glebe and Leggett (1981) determined that to reach spawning grounds, American shad in the St. Johns River, Florida expended 70-80% of their total energy reserves (entirely semelparous population). In comparison, York River, Virginia individuals expended approximately 30% of their energy reserves (25% iteroparous population), and 40-60% individual energy expenditure occurred in the Connecticut River (35% iteroparous population; Glebe and Leggett 1981). Migration distance and speed, along with river gradient were the primary factors in energy expenditures (Glebe and Leggett 1981). In the Connecticut River, Leonard and McCormick (1999) found total energy depletion ranged from 35 to 61% to migrate 228 rkm to spawning grounds (~25 kJ/km/fish), with differences between sexes, sizes, and years. The authors stated an iteroparity threshold may occur in the range 35 to 40% of energy expenditure (Leonard and McCormick 1999). American shad emigrating from the Little River must migrate an additional 212 rkm through the Neuse River, suggesting that total spawning survival to the ocean may be lower than estimated.

Annual iteroparity rates were low in the Little River. American shad are known to return to their natal river and in subsequent years (Melvin 1986), but I documented the first known tagged individuals to return to a North Carolina river in a subsequent year. However, despite large emigration events in 2008 and 2009 when many American shad were tagged, a very limited number returned in 2009 and 2010 (<1%). The low iteroparity rate may be due to additional energy expenditure and predation in the Neuse River, combined with natural and fishing mortality in the ocean. Based on scale marks, Walburg (1957) determined that
repeat spawners comprised less than 3% of the 1953 American shad run in the Neuse River. Also based on scale marks, repeat spawners comprised between 0 and 23% of the total annual male catch and 0 to 41% of the total annual female in the Neuse River commercial fishery from 1977 to 2005 (ASMFC 2007).

I observed a few dead American shad throughout the river, including downstream of Atkinson Mill Dam. Similar to Walburg (1960), dead American shad typically sunk to the bottom of the Little River. I also observed snapping turtles *Chelydra serpentina* and great blue herons *Ardea herodias* consuming dead individuals and Walburg (1960) noted white pelicans *Pelecanus erythrorhynchos* consumed weak and dying American shad in the St. Johns River, Florida. In addition, I observed predation and predation attempts by flathead catfish, common snapping turtle, and great blue heron on live American shad. This highlights the importance of American shad as marine derived nutrients into freshwater systems (Garman and Macko 1998). These observations may explain why, unlike Chittenden (1976), few carcasses are seen in southern rivers.

*Abundance*

Increasing population size is the primary goal of restoration efforts. Due to difficulty in estimating populations, relative abundance metrics and fish passage numbers are more commonly used to assess American shad abundance. Harris and Hightower (2012) estimated the Roanoke River American shad population at 5,224 females based on female fecundity, egg to fry survival rates, and estimated wild fry produced in a year. However, relatively little is known about American shad population sizes in tributaries. My initial goal to conduct a
census of the Little River population at the fish weir proved unfeasible due to flooding and weir failures. The number of American shad sampled at the weir provided a minimum estimate of the population size and from 2007 through 2010. In population estimates, I attempted to account for unsampled individuals that either died upstream or were missed at the weir. American shad population estimates ranged from 3,512 to 10,155 in the Little River. Estimates displayed an increasing trend from 2007 to 2009, but decreased in 2010. The low estimate in 2010 may be a real trend or due to other factors such as natural variability. In addition, the estimation method was very sensitive to the number of untagged emigrating individuals that was a very low number in 2010, potentially due to higher mortality during extended low mid-season flows and the highest flathead catfish abundance. Estimated population sizes increased noticeably in each year, exceeding the Roanoke River estimate (Harris and Hightower 2012) in 2007 through 2009 and the 49/ha conservative guideline for a healthy population (Savoy and Crecco 1994) in 2008 and 2009. However, all estimates were still at least 50% below the 124/ha guideline (St. Pierre 1979). It is possible the Little River American shad population may not increase substantially post-dam removals due to other limiting factors (e.g., degraded spawning habitat, poor juvenile habitat, predation, ocean harvest). However, it is also possible large river guidelines estimated in northern rivers do not apply to tributaries or southern rivers. Another potential explanation is that sufficient time has not passed for the population to rebuild (Hasselman and Limburg 2012). American shad first mature into spawning adults between ages three and six (Walburg and Nichols 1967). Dam removals commenced in 1998, with the furthest upstream habitat unavailable until Lowell Mill Dam was removed in the winter of 2005. Therefore,
individuals benefiting from access to restored upstream habitat (e.g., higher egg hatching rates, increased survival/growth rates of young) in 2006 would first return, at the earliest, as mature adults in 2009. As such, a positive population response to the dam removals may not yet be apparent.

Flathead Catfish Predation

Flathead catfish appear capable of influencing American shad restoration efforts based on the estimated maximum Little River consumptions. I estimated sampled flathead catfish could consume approximately five to nine percent of the sampled and one to two percent of the estimated Little River American shad population in 2009. However, in 2010 estimated predation by sampled flathead catfish accounted for 22 to 44% of the sampled population and seven to 13% of the estimated American shad population. When including the estimated total number of flathead catfish in 2010, they could potentially consume all sampled American shad and between 18 and 36% of the estimated population. Pine et al. (2007) estimated flathead catfish could reduce total fish biomass by 5-50% through both predation and competition. In my estimations, I assumed flathead catfish consumed only American shad in the Little River. While this is unlikely because flathead catfish display non-selective feeding behaviors (Pine et al. 2005; Baumann and Kwak 2011), it is plausible that American shad were the primary prey due to their abundance, temporal and spatial overlap (especially in downstream reaches), and increased vulnerability due to physical exhaustion, particularly in May when the most flathead catfish were in the Little River. In the Cape Fear River, Ashley and Buff (1987) found American shad accounted for 4.6% of
total prey items and 50.7% of total weight in flathead catfish stomachs despite being consumed in only two months (April and May) of a six-month study.

The maximum potential number of American shad consumed by flathead catfish could actually be higher than estimated. If smaller American shad were targeted by flathead catfish, estimated numbers would increase because I divided the total estimated biomass consumed by the median American shad weight. Similarly, if the large proportion of the 2010 flathead catfish size distribution estimated to be too small actually were capable of consuming American shad, estimates would noticeably increase. In at least one documented predation event a flathead catfish consumed an American shad larger than its estimated gape width. Also, daily adult consumption rates could potentially be higher than juvenile rates (Bourret et al. 2008) used in estimations. Bourret et al. (2008) noted southern flathead catfish populations might feed at different rates than northern populations used in their study. Baumann and Kwak (2011) estimated a daily flathead catfish consumption rate of 3.06% of body weight in July (26 °C) in a North Carolina field study, within the range (0.82 – 3.33% at 26 °C) of the Bourret et al. (2008) laboratory study but higher than the predicted value (2.24%) for that temperature in this study.

The documented cases of predation and consumption estimates, regardless of the exact number, indicate expanding flathead catfish populations can negatively influence American shad restoration efforts. In the Little River, American shad migrating during cool temperatures (<15 °C) and into upstream reaches may avoid flathead catfish predation. Conversely, flathead catfish would have the most impact on American shad migrating late in the season (i.e., May) and remaining in downstream reaches. Emigrating individuals also are
vulnerable, but at least had the opportunity to spawn and Little River iteroparity rates appear low. Pine et al. (2007) estimated that sustained, annual removal (6-25%) of flathead catfish could noticeably reduce their influence on the native fish community. In addition to reducing flathead catfish abundance, decreasing their age and size distributions through continued removal of older, large individuals could limit their American shad consumption potential. Based on Kwak et al. (2006), a 636 mm Neuse River flathead (capable of consuming minimum American shad size) would be between age 6 and 7, while a 917 mm individual (capable of consuming all American shad size) would be between age 12 and 13. The fish weir captured a variety of flathead catfish sizes and could be used as a removal tool, especially considering 72% of individuals tagged in 2009 returned to the Little River in 2010. Encouraging recreational anglers to harvest flathead catfish, or developing commercial fisheries could benefit concurrent restoration efforts of American shad populations.

Conclusions

Although American shad have received extensive study for over a century (e.g., Stevenson 1899) the present research provided new information on spawning behavior and migrations relative to environmental conditions in a river with multiple dam removals and is the first to estimate spawning season survival rates, determine individual weight loss, and estimate predation by introduced flathead catfish. The fish weir was effective at capturing American shad while PIT technology allowed thousands of individuals to be tagged and monitored, including repeat spawners. Efficiency decreased at high flows, an issue common to most gears. During freshets, American shad tended to migrate into upstream reaches with
higher habitat complexity that may be optimal spawning and nursery habitat. Future studies evaluating survival of eggs (rather than adult presence and egg deposition) and young survival and growth would greatly aid habitat identification, protection, and restoration efforts. River flow conditions strongly influenced American shad spawning migrations and behaviors. Annual flow patterns may factor into use of restored habitat, reproductive output, and adult survival. This information could potentially be used to predict annual reproductive output and also incorporated into flow regimes of regulated rivers. In the Little River, American shad weight loss was considerable, with water temperature and duration in the river appearing to be the driving factors. Weight loss likely factors into American shad survival, so efforts to decrease migratory impediments and delays at anthropogenic and natural obstructions would be beneficial. The Little River American shad population appears to be healthy as two annual estimates exceeded the conservative guideline. A follow-up study, after multiple generations have had access to restored habitat, would further examine the success of restoration efforts. Similarly, additional research on flathead catfish consumption on American shad could reduce assumptions and improve estimates. Nevertheless, flathead catfish predation on American shad raises concerns and may be an area to increase management efforts to restore economically and ecologically important American shad populations.
REFERENCES


Harris, J. E., and J. E. Hightower. 2012. Demographic population model for American shad: will access to additional habitat upstream of dams increase population sizes? Marine and Coastal Fisheries 4:262-283.


Table 3.1. Total American shad sampled (including recaptures) and number of functioning sampling days at the fish weir from 2007 to 2010 in the Little River.

<table>
<thead>
<tr>
<th>Year</th>
<th>Sampling days</th>
<th>American shad captured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Upstream</td>
</tr>
<tr>
<td>2007</td>
<td>64</td>
<td>46</td>
</tr>
<tr>
<td>2008</td>
<td>61</td>
<td>137</td>
</tr>
<tr>
<td>2009</td>
<td>50</td>
<td>474</td>
</tr>
<tr>
<td>2010</td>
<td>70</td>
<td>853</td>
</tr>
<tr>
<td>Total</td>
<td>245</td>
<td>1510</td>
</tr>
</tbody>
</table>

Table 3.2. American shad sex ratio (female:male) relative to year, upstream and downstream capture, and month in the Little River. Fish weir was located at rkm 56.4 in 2007 and rkm 3.7 in 2008 through 2010.

<table>
<thead>
<tr>
<th>Year</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream</td>
<td>Downstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>0.75 (7)</td>
<td>0.74 (33)</td>
<td>0.51 (62)</td>
<td>0.37 (491)</td>
</tr>
<tr>
<td>2008</td>
<td>0.32 (29)</td>
<td>0.56 (89)</td>
<td>1.26 (167)</td>
<td>0.89 (183)</td>
</tr>
<tr>
<td>2009</td>
<td>0.67 (10)</td>
<td>0.75 (7)</td>
<td>1.40 (230)</td>
<td>1.43 (165)</td>
</tr>
<tr>
<td>2010</td>
<td>0.44 (46)</td>
<td>0.61 (129)</td>
<td>1.33 (459)</td>
<td>0.60 (839)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream</td>
<td>Downstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>0.00 (4)</td>
<td>0.86 (26)</td>
<td>0.67 (5)</td>
<td>0.60 (8)</td>
</tr>
<tr>
<td>2008</td>
<td>1.19 (226)</td>
<td>1.01 (632)</td>
<td>1.63 (189)</td>
<td>1.15 (103)</td>
</tr>
<tr>
<td>2009</td>
<td>0.49 (191)</td>
<td>0.87 (305)</td>
<td>1.41 (1359)</td>
<td>1.36 (106)</td>
</tr>
<tr>
<td>2010</td>
<td>0.79 (421)</td>
<td>0.96 (963)</td>
<td>1.43 (1553)</td>
<td>1.23 (217)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>0.76 (513)</td>
</tr>
<tr>
<td>2008</td>
<td>0.91 (2184)</td>
</tr>
<tr>
<td>2009</td>
<td>1.41 (4024)</td>
</tr>
<tr>
<td>2010</td>
<td>0.71 (2112)</td>
</tr>
</tbody>
</table>
Table 3.3. Total length and weight of female and male American shad measured in 2008 through 2010. Letters represent significant difference (p <0.05) within grouping.

<table>
<thead>
<tr>
<th></th>
<th>Total length (mm)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean</td>
</tr>
<tr>
<td>Female upstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>147</td>
<td>492.2</td>
</tr>
<tr>
<td>April</td>
<td>205</td>
<td>486.1</td>
</tr>
<tr>
<td>May</td>
<td>230</td>
<td>484.3</td>
</tr>
<tr>
<td>Female downstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>4</td>
<td>509.3</td>
</tr>
<tr>
<td>April</td>
<td>223</td>
<td>480.0</td>
</tr>
<tr>
<td>May</td>
<td>519</td>
<td>476.0</td>
</tr>
<tr>
<td>Male upstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>365</td>
<td>430.9</td>
</tr>
<tr>
<td>April</td>
<td>221</td>
<td>422.5</td>
</tr>
<tr>
<td>May</td>
<td>148</td>
<td>424.8</td>
</tr>
<tr>
<td>Male downstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>6</td>
<td>444.7</td>
</tr>
<tr>
<td>April</td>
<td>157</td>
<td>423.2</td>
</tr>
<tr>
<td>May</td>
<td>446</td>
<td>423.3</td>
</tr>
</tbody>
</table>

Table 3.4. American shad spawning season survival estimates in the Little River from 2007 through 2010. Weir method used tagged individuals upstream for at least 24 hours, weir and antenna and Cormack-Jolly-Seber (CJS) model methods used only individuals detected at rkm 13.4 or upstream. Note: CJS weekly estimate SE: 2009=0.00042, 2010=0.00009.

<table>
<thead>
<tr>
<th>Year</th>
<th>Weir (upstream ≥24 h)</th>
<th>Weir &amp; antennas (&gt;rkm 13.4)</th>
<th>Weekly CJS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tagged</td>
<td>Recaptured</td>
<td>Estimate</td>
</tr>
<tr>
<td>2007</td>
<td>21</td>
<td>8</td>
<td>0.238</td>
</tr>
<tr>
<td>2008</td>
<td>82</td>
<td>15</td>
<td>0.098</td>
</tr>
<tr>
<td>2009</td>
<td>364</td>
<td>60</td>
<td>0.165</td>
</tr>
<tr>
<td>2010</td>
<td>703</td>
<td>72</td>
<td>0.084</td>
</tr>
</tbody>
</table>
Table 3.5. Proportions of male and female American shad initiating a downstream migration and migrating to rkm 7.7 or downstream relative to their maximum upstream reach in 2009 and 2010 in the Little River.

<table>
<thead>
<tr>
<th>Reach (rkm)</th>
<th>Female 2009</th>
<th>Male 2009</th>
<th>Female 2010</th>
<th>Male 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n Initiated</td>
<td>&lt; 7.7</td>
<td>n Initiated</td>
<td>&lt; 7.7</td>
</tr>
<tr>
<td>7.7 - 13.4</td>
<td>50</td>
<td>0.22</td>
<td>18</td>
<td>0.22</td>
</tr>
<tr>
<td>13.4 - 45.3</td>
<td>45</td>
<td>0.24</td>
<td>30</td>
<td>0.27</td>
</tr>
<tr>
<td>45.3 - 56.4</td>
<td>2</td>
<td>0.50</td>
<td>2</td>
<td>0.50</td>
</tr>
<tr>
<td>56.4 - 72.0</td>
<td>6</td>
<td>0.17</td>
<td>13</td>
<td>0.08</td>
</tr>
<tr>
<td>72.0 - 77.0</td>
<td>11</td>
<td>0.09</td>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td>77.0 - 82.3</td>
<td>4</td>
<td>0.00</td>
<td>12</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 3.6. Number of sampled and estimated American shad in 2007 through 2010 in the Little River compared to guidelines for healthy populations. Any individuals that entered the river but did not migrate to the weir (rkm 56.4 in 2007, rkm 3.7 in 2008-2010) would not have been sampled. The impassable Atkinson Mill Dam (rkm 82.3) represented the upper extent of available habitat.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Length (rkm)</th>
<th>Area (ha)</th>
<th>Guideline</th>
<th>American shad sampled (estimated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(49/ha)</td>
<td>(124/ha)</td>
<td>2007</td>
</tr>
<tr>
<td>Mouth - dam</td>
<td>82.3</td>
<td>184.0</td>
<td>9016</td>
<td>22814</td>
</tr>
<tr>
<td>Weir - dam</td>
<td>25.9</td>
<td>51.1</td>
<td>2504</td>
<td>6342</td>
</tr>
<tr>
<td>Weir - dam</td>
<td>78.5</td>
<td>174.9</td>
<td>8570</td>
<td>21692</td>
</tr>
</tbody>
</table>
Table 3.7. Estimated number of American shad in different Little River reaches based on migratory distributions in 2009 and 2010 compared to two rules-of-thumb.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Start (rmk)</th>
<th>Length (rmk)</th>
<th>Area (ha)</th>
<th>Guideline 49/ha</th>
<th>124/ha</th>
<th>Estimated number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldsboro - Forest Service</td>
<td>7.7</td>
<td>5.7</td>
<td>12.0</td>
<td>588</td>
<td>1487</td>
<td>3554</td>
</tr>
<tr>
<td>Forest Service - Rains Crossroads</td>
<td>13.4</td>
<td>31.9</td>
<td>77.8</td>
<td>3814</td>
<td>9651</td>
<td>3960</td>
</tr>
<tr>
<td>Rains Crossroads - Lowell Mill</td>
<td>45.3</td>
<td>11.1</td>
<td>23.6</td>
<td>1154</td>
<td>2921</td>
<td>203</td>
</tr>
<tr>
<td>Lowell Mill - Shoeheel Road</td>
<td>56.4</td>
<td>15.6</td>
<td>33.1</td>
<td>1623</td>
<td>4107</td>
<td>1016</td>
</tr>
<tr>
<td>Shoeheel Road - Old Dam Road</td>
<td>72.0</td>
<td>5.0</td>
<td>7.9</td>
<td>387</td>
<td>979</td>
<td>609</td>
</tr>
<tr>
<td>Old Dam Road - Atkinson Mill</td>
<td>77.0</td>
<td>5.3</td>
<td>10.1</td>
<td>496</td>
<td>1256</td>
<td>812</td>
</tr>
</tbody>
</table>

Table 3.8. Estimated number of American shad consumed by different flathead catfish size categories for individuals sampled in 2009 and 2010 and estimated total individuals in 2010 in the Little River.

<table>
<thead>
<tr>
<th></th>
<th>Min.</th>
<th>25%</th>
<th>Median</th>
<th>75%</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>American shad length distribution (mm)</td>
<td>346</td>
<td>425</td>
<td>455</td>
<td>482</td>
<td>575</td>
</tr>
<tr>
<td>Capable flathead catfish length (mm)</td>
<td>636</td>
<td>740</td>
<td>778</td>
<td>810</td>
<td>917</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampled flathead catfish</td>
<td>50</td>
<td>35</td>
<td>32</td>
<td>30</td>
<td>17</td>
</tr>
<tr>
<td>Estimated biomass consumed (kg)</td>
<td>137.7</td>
<td>118.2</td>
<td>113.3</td>
<td>109.0</td>
<td>76.8</td>
</tr>
<tr>
<td>Estimated American shad consumed</td>
<td>193</td>
<td>166</td>
<td>159</td>
<td>153</td>
<td>108</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampled flathead catfish</td>
<td>146</td>
<td>87</td>
<td>79</td>
<td>74</td>
<td>54</td>
</tr>
<tr>
<td>Estimated biomass consumed (kg)</td>
<td>338.0</td>
<td>241.0</td>
<td>236.3</td>
<td>219.7</td>
<td>170.2</td>
</tr>
<tr>
<td>Estimated American shad consumed</td>
<td>472</td>
<td>336</td>
<td>330</td>
<td>306</td>
<td>237</td>
</tr>
<tr>
<td>Estimated flathead catfish</td>
<td>395</td>
<td>236</td>
<td>214</td>
<td>200</td>
<td>146</td>
</tr>
<tr>
<td>Estimated biomass consumed (kg)</td>
<td>915.5</td>
<td>652.8</td>
<td>640.0</td>
<td>595.1</td>
<td>461.0</td>
</tr>
<tr>
<td>Estimated American shad consumed</td>
<td>1278</td>
<td>911</td>
<td>893</td>
<td>831</td>
<td>643</td>
</tr>
</tbody>
</table>
Figure 3.1. Map of the Little River, North Carolina, depicting dam locations and status (year removed, notched, present) and passive integrated transponder (PIT) antennas in 2009-2010. The fish weir was located at rkm 56 in 2007 and rkm 4 in 2008-2010.
Figure 3.2. Upstream and downstream captures of female and male American shad relative to flow and water temperature at the Little River fish weir located at rkm 56.4 in 2007 and rkm 3.7 in 2008.
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American shad diel activity at antennas in different Little River reaches in 2009 and 2010.

**Figure 3.11.** American shad diel activity at antennas in different Little River reaches in 2009 and 2010.
Figure 3.12. American shad diel activity at antennas in 2009 and 2010 during different Little River flow quartiles (March-May in 2000 to 2010).
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Figure 3.15. Little River flathead catfish size distribution in 2010 and the estimated proportion of the American shad size distribution (2008-2010) that different flathead catfish sizes could consume based on estimated flathead catfish gape widths and American shad body depths.
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Figure 3.17. Spatial and temporal overlap of flathead catfish and American shad in the Little River in 2010. Captured and detected individuals were counted once per day at each location. Note: dashed line represents change in scale.
CHAPTER 4
A Spatial Capture – Recapture Model to Estimate Fish Survival and Migration Patterns from Linear Continuous Monitoring Arrays

ABSTRACT
Advances in telemetry technology, including smaller transmitters and continuous monitoring stations, allow researchers to collect spatial data on tagged individuals. Statistical models capable of using all data points and estimating both spatial and demographic parameters have been lacking. I developed a linear spatial capture-recapture model to evaluate survival and movement of migratory fishes, and demonstrate the model using data for American shad *Alosa sapidissima* in a North Carolina river. Using a resistance board weir near the river mouth, I tagged individuals with passive integrated transponders (PIT) in the spring of 2010 and passively monitored migrations with an array of PIT antennas. The river channel constrained migrations, resulting in linear, one-dimensional data. My spatially explicit version of the Cormack-Jolly-Seber model incorporated both weir captures and antenna detections and was analyzed using a Bayesian framework and implemented in JAGS software. Survival and activity centers (i.e., mean location) were estimated each time period with associated uncertainty (i.e., credible intervals). The model estimated a weekly survival of 0.80 for American shad, indicating high spawning mortality. Activity centers and a movement parameter (σ) showed that river conditions (gage height) influenced the extent of weekly American shad migrations; individuals migrated greater distances in higher flows. This model is applicable for any linear array (e.g., rivers, shorelines, corridors), opening new opportunities to study demographic parameters, movement or migration, and habitat use.
INTRODUCTION

Continued advances in fish tagging technology allow researchers to collect an ever-expanding amount of data on tagged individuals (Lucas and Baras 2000; Heupel et al. 2006; Rogers and White 2007). For example, telemetry transmitters are decreasing in physical dimensions while increasing in battery capacity and signal strength, providing opportunities to study fishes of varying sizes over extended durations and from longer ranges (Lucas and Baras 2000; Heupel et al. 2006; Heupel and Webber 2012). Passive integrated transponders (PIT) permit the study of numerous fish species, sizes, and individuals over the course of their lifetimes as the tags are small, relatively inexpensive, and lack batteries (Prentice et al. 1990; Castro-Santos et al. 1996; Lucas and Baras 2000). Yet, the greatest increase in the data collection potential corresponds with the advent of continuous monitoring stations (e.g., acoustic telemetry receivers, PIT antennas) that passively detect individuals (Castro-Santos et al. 1996; Lucas and Baras 2000; Heupel and Webber 2012). These systems greatly increase “recaptures” without physically handling fish, creating temporal and spatial individual encounter histories (Zydlewski et al. 2006; Hewitt et al. 2010). However, errors in detection still exist and should be handled directly.

Quantitative methods to analyze fisheries data obtained from continuous monitoring systems are also advancing, but at a slower pace than tagging and computing technologies (Heupel et al. 2006). Most often, descriptive statistics, plots, and maps are used to summarize habitat use, distributions, migrations, and fish passage rates (Rogers and White 2007). Habitat use and home ranges have also been evaluated with geographic information systems (GIS) and position averaging techniques (Simpfendorfer et al. 2002; Rogers and
To estimate demographic parameters, capture-recapture models, in particular the “Jolly-Seber” (JS) and “Cormack-Jolly-Seber” (CJS) models (Cormack 1964; Jolly 1965; Seber 1965), use individual encounter histories to estimate abundance and apparent survival (mortality plus emigration) even with imperfect detection rates (Pollock et al. 1990; Williams et al. 2002; Pine et al. 2003). These capture-recapture models have successfully been used in fish studies with continuous monitoring stations (Skalski et al. 1998; Hewitt et al. 2010). However, information is lost in capture-recapture models when data are consolidated into a single observed / not observed binary datum in either temporal (e.g., Hewitt et al. 2010) or spatial (e.g., Skalski et al. 1998) intervals (Gardner et al. 2010). Spatial multistate models are an extension of capture-recapture models that estimate apparent survival along with transition (migration) probabilities into different states such as river reaches (Lebreton and Pradel 2002; Schwarz 2009). Challenges with multistate models include being data intensive, often limiting them to a few states and time periods; a detected individual can be classified into only one state per time period, a potential issue for highly migratory species (Lebreton and Pradel 2002). As such, few multistate fisheries models exist, especially those using continuous monitoring stations (Buchanan and Skalski 2009; Horton et al. 2011).

An ideal statistical model for continuous monitoring station studies would use all collected data to estimate both spatial and demographic parameters in a robust manner. Heupel et al. (2006) recommended examining literature outside of aquatic sciences for options to analyze telemetry data. A review of terrestrial literature shows a variety of 2-dimensional spatial capture-recapture models for fixed continuous monitoring stations (e.g., camera traps, hair snares) arranged in a spatial grid (e.g., latitude, longitude; Karanth et al.
Recent models estimate survival, abundance and density, and also individual “activity centers” that estimate the mean spatial location in a time period and are conceptually similar to home range centers (Gardner et al. 2009; Royle et al. 2009; Gardner et al. 2010). In Gardner et al. (2010), the individual encounter histories are arranged as the number of detections for each individual, at each sampling location, in each time period; all spatial and temporal data are analyzed. Aquatic studies with an analogous spatial grid of continuous monitoring stations (e.g., estuary, marine protected area, lake) can use these models. However, these models would not apply to aquatic studies where the continuous monitoring stations are arranged in a linear array (e.g., rivers, shorelines, migratory paths).

In this chapter, I developed a linear spatial capture-recapture model to evaluate American shad *Alosa sapidissima* survival and movement in a North Carolina river with a linear array of PIT antennas. I used the basic framework of the Gardner et al. (2010) terrestrial spatial capture-recapture model, but made two significant changes. I used a CJS formulation of the open model with staggered entry and, because the river constrained movement to a linear manner, the continuous monitoring stations were treated in 1-dimension (i.e., river kilometer, rkm) instead of 2-dimensions (e.g., latitude, longitude). I also correlated the individual activity centers to the previous location of the tagged fish and incorporated river conditions (i.e., gage height) as a covariate. This model is flexible and applicable to other aquatic and terrestrial studies using linear continuous monitoring stations, and potentially applicable to solely physical capture-recapture studies.
METHODS

Study Site

The Little River is a fourth order tributary to the Neuse River, with the confluence near Goldsboro, North Carolina (Figure 4.1). The rivers meet approximately 212 river kilometers (rkm) from Pamlico Sound. Three low head (≤4 m in height), run-of-river dams were recently removed from the Little River, another dam was partially removed; upstream intact dams still exist (Raabe, Chapter 2).

Study Species

Populations of anadromous American shad, native to the Atlantic coast of North America, migrate from the ocean into rivers in late winter (e.g., St. Johns River, Florida) through early summer (e.g., St. Lawrence River, Canada; Limburg 2003). These migrations are energetically expensive and may lead to substantial spawning mortality because minimal feeding occurs in rivers (Chittenden 1976; Leggett and Carscadden 1978; Leonard and McCormick 1999). American shad survival is believed to vary latitudinally; southern populations die after spawning once (semelparous) while northern populations may spawn multiple times (iteroparous), with a transition zone thought to occur in North Carolina (Leggett and Carscadden 1978). However, no studies have empirically estimated within river survival rates.

American shad populations are currently at historic low levels (Limburg 2003; ASMFC 2007; Limburg and Walden 2009) but are the focus of considerable restoration efforts due to their ecological importance in both freshwater and marine systems (e.g., prey
items, nutrient transport; Garman and Macko 1998) and the valuable commercial fishery they once supported (Hightower et al. 1996; Limburg 2003). Population declines are commonly attributed to overfishing along with general habitat degradation and dams restricting access to habitat (Hightower et al. 1996; Cooke and Leach 2003; St. Pierre 2003). Dam removal efforts often focus on increasing connectivity to upstream spawning habitat for American shad and other anadromous fishes, but only a few studies have evaluated the effectiveness of this approach (Weaver et al. 2003; Burdick and Hightower 2006). In addition, the study of American shad migratory patterns and their relationship with environmental conditions have focused on general trends (e.g., catch rates instead of multiple capture-recaptures) or a limited number of fish (e.g., telemetry).

Data Collection

I used a resistance board fish weir to capture and tag American shad in the springs of 2007 through 2010 (Raabe, Chapter 2), but am focusing on 2010 for the linear spatial capture-recapture model. The fish weir was installed at the former Cherry Hospital Dam site (rkm 3.7), allowing me to tag immigrating fish prior to migrations, censor emigrating fish, and install an array of upstream PIT antennas (Figure 4.1). I inserted a small (3.9 mm x 31.2 mm, 0.8 g) Texas Instruments PIT tag (RI-TRP-RE2B) into the abdominal cavity of all visibly healthy, immigrating American shad via a small incision between the pectoral and pelvic fins; this rapid procedure required no anesthetic. I scanned all captured fish with a handheld PIT reader (Allflex Compact Reader RS200).
I installed six PIT antennas (Raabe, Chapter 2) as continuous monitoring stations to detect American shad during their migrations in the Little River (Figure 4.1). My antenna site selection criteria included proximity to dam sites and overall river coverage, but options were limited by permissible access and suitable river channel characteristics for installation.

Water gage height data (m) were recorded hourly immediately downstream of the weir site at a United States Geological Survey (USGS) monitoring station (0208863200).

Model Development

I modeled the Little River as an open system due to mortalities and because the weir did not provide complete closure during high flow events. I followed the framework of the open spatial capture-recapture model in Gardner et al. (2010) but instead of the JS type model used to estimate density, recruitment, and survival, I used a CJS type model to focus on survival and movement. The main components of the linear spatial capture-recapture model are an observational model based on weir captures and antenna detections, a state model based on whether an individual is estimated alive or not, and latent activity centers.

In the observational model, encounter histories ($y(i,j,t)$) are the counts of observations for each individual ($i = 1, 2, \ldots, n$), at each location ($j = 1, 2, \ldots, J$), during each sample occasion ($t = 1, 2, \ldots, T$). When no observations occurred, ($y(i,j,t) = 0$). I assigned each sampling location ($j$) a linear (i.e., rkm) coordinate ($x(j)$). Observations occurred as both weir captures ($x(1)$: rkm 3.7) and detections at PIT antennas ($x(2-7)$: rkm 7.7, 13.4, 45.3, 56.4, 72.0, 77.0) at a total of seven locations ($J = 7$). I used a weekly interval for sampling occasions ($t$), with a total of 12 occasions ($T = 12$). Weir observations were limited to a
capture and tagging event during upstream immigration and a recapture during downstream emigration, at which point the individual was censored from future sampling periods. Each tagged individual could be detected at any functioning antenna, any number of times, during a particular week.

The observational model is conditional on an individual’s estimated “alive state” \( z \) in the state model. For each individual \( i \) during each time period \( t \), the “alive state” \( z \) describes whether it is alive and in the river \( z(i, t) = 1 \) or not alive / in the river \( z(i, t) = 0 \). Upon river entry, a tagged individual fish is known to be alive and in the river, so in its first period \((i, f_i)\) the initial alive state is

\[
z(i, f_i) = 1
\]

where the probability of being alive is 1. Individuals clearly emigrating from the river were censored after their last period \((l_i)\) in the river while the final study period \((T)\) was the last period for all other individuals. After the river entry period, the alive state is estimated by

\[
\text{for } t(f_i - l_i), \ z(i, t) \sim \text{Bernoulli}(\phi z(i, t - 1))
\]

where the individual may survive with probability \( \phi \) when \( z(i, t - 1) = 1 \). The apparent survival probability \( \phi \) is estimated as a constant across individuals and time periods due to relatively sparse encounter histories for certain American shad. To account for staggered entries and censoring, I assigned a \( z = 0 \) (i.e., not in river) for periods prior to river entry \((t < f_i)\) and after documented emigrations \((t > l_i)\).

Weekly American shad weir captures were binary (captured / not captured) and the observations were modeled as
\[ y(i,j,t) \mid z(i,t) \sim \text{Bernoulli}\left((1 - \exp(-\lambda_0)) \cdot g(i,j,t) \cdot z(i,t)\right) \]

whereas individuals could be detected multiple times at any functioning antenna during a weekly period, the observations are modeled with Poisson random variables

\[ y(i,j,t) \mid z(i,t) \sim \text{Poisson}\left(\lambda_0 \cdot g(i,j,t) \cdot z(i,t)\right) \]

where the encounter histories \((y(i,j,t))\) are conditional on the latent state variable \((z(i,t))\) in both the Bernoulli and Poisson versions. When \(z(i,t) = 1\), an individual \((i)\) is estimated to be alive in time period \((t)\) and the observations are Bernoulli (weir) or Poisson (antennas).

When \(z(i,t) = 0\), an individual \((i)\) is inferred to either be not alive or not in the river in time period \((t)\), and the observations must be zero with a probability of 1. The function \(g\) is a general distance function commonly used in distance and other sampling approaches (Buckland et al. 2001; Efford 2004; Gardner et al. 2010). It is assumed that \(g(i,j,t) = g(s(i,t), x(j)) = \exp(-d(i,j,t)^2/2\sigma^2)\), where \(d(i,j,t) = \| s(i,j,t) - x(j) \|\) is the distance between an estimated individual activity center \((s(i,t))\) and each sampling location \((x(j))\) in a time period \((t)\), while \(\sigma\) is a shape parameter for the decline in the distance function \((g)\). The parameter \(\sigma\) determines the detection rate at a sampling location \((x(j))\) as a function of distance from the activity center \((s(i,t))\). Royle and Young (2008) suggested that \(\sigma\) could be associated with movement or home range calculations. For example, as \(\sigma\) increases, the decline function becomes more gradual and a tagged individual is more likely to move enough within a period to be detected at one or more sampling locations \((x(j))\). The parameter \(\lambda_0\) is a baseline encounter rate, it estimates the expected number of observations (capture, detections) when an individual’s activity center \((s(i,t))\) is precisely at a particular sampling location \((x(j))\). A
small $\lambda_0$ (e.g., 0.1) may indicate stationary or elusive individuals or detection probability issues (e.g., mechanical failures) whereas a larger $\lambda_0$ (e.g., 1.0) implies an individual will likely be observed at a sampling site ($x(j)$) when located at the individual’s activity center ($s(i,t)$).

I modified the base model described above to account for American shad behaviors and Little River sampling gear. American shad made extensive migrations in higher flows and were detected less often in low flows (Raabe, Chapter 2). I modeled weekly $\sigma$ as $\log(\sigma_t) = \beta_0 + \beta_1 gage_t$ where $\beta_0$ is the intercept and $\beta_1$ is the coefficient for mean weekly gage height (m). I modeled the encounter rate ($\lambda_0$) as time dependent and separately by gear (weir $\lambda_{0w}$, antenna $\lambda_{0a}$) because weir captures were binary and the number of weekly antenna detections varied but did not appear to have a direct relationship with flow or other covariates (e.g., water temperature). Sampling gear had failure periods, primarily during high flow events that flooded the weir and decreased antenna efficiencies (Raabe, Chapter 2). To inform the model of these failure periods, I included the proportion of days in a week that gear at each sampling location ($x(i,t)$) worked properly (e.g., 0.71 for five functioning days).

Individual activities centers ($s(i,t)$) within the overall state-space ($S$) are unknown and thus must be estimated within the model (Efford 2004; Royle and Young 2008; Gardner et al. 2010). The Little River state-space $S$ ranged from the river mouth (rkm 0) to the most downstream dam, Atkinson Mill Dam (rkm 82), containing all river habitat available to American shad during their spawning migrations. I used three different models with different distributions (uniform, normal, truncated normal) to estimate individual activity centers. For all three models, in an individual’s first time period activity centers were
assumed to be distributed uniformly over the state-space (Efford 2004; Royle and Young
2008; Gardner et al. 2010) such that

\[ s(i, f_i) \sim Uniform(x_l, x_u) \]

where the uniform distribution is bounded by the state-space coordinates. Subsequent
periods were estimated in this manner in the uniform model. For the normal model,
subsequent activity centers were correlated by defining \((s(i, t))\) as drawn from a normal
distribution where the mean is the previous activity center \((s(i, t-1))\) and an estimated constant
variance \((\tau)\). This informed the model of an individual’s previous location and provided a
way to estimate activity centers in time periods when an individual was not observed. In the
truncated normal model, subsequent activity centers were estimated as

\[ for \ t(f_i - l), s(i, t) \sim Normal(\mu(s(i, t-1), \tau I) \mid \mu, \sigma) \]

where the normal distribution was truncated, or bounded, by the state-space coordinates.

**Data Preparation**

Two important assumptions of capture-recapture models are that tagging does not
influence the recapture probability of an individual (including mortality) and that tags are not
lost or missed (Pollock et al. 1990; Williams et al. 2002). I was unable to estimate tagging
mortality or tag loss rates, therefore, I only included individuals detected at antennas located
at or upstream of rkm 13.4 with at least two observations (e.g., weir and antenna detection). I
assumed these fish were healthy and retained their tags because they migrated 10 rkm or
more post-tagging; delayed tag loss was still a possibility but is typically low with PIT tags
(Prentice et al. 1990; Gries and Letcher 2002). Returning American shad (tagged in 2009)
clearly retained their tags and were healthy; I included three returning American shad detected at multiple antennas but excluded two returning individuals detected only once. A total of 315 American shad were included.

I constructed American shad encounter histories as the count of individual captures at the weir and detections at each antenna within a weekly time period, resulting in a 3-dimensional dataset of capture / detection frequencies (individual x antenna x week). To limit repetitive detections at an antenna (e.g., tagged fish resting near an antenna), I included only the first detection when additional subsequent detections occurred within 30 minutes; this differs slightly from one count per 30-minute bins. For example, if a fish was detected at an antenna at 7:55, 8:05, 8:20, and 8:35, I counted two detections (7:55, 8:35) whereas 30-minute bins would result in three detections (7:55, 8:05 or 8:20, 8:35). I divided the spawning season into 12 weekly periods, starting on 10 March 2010 and ending on 1 June 2010. During this time, the fish weir and all antennas were installed (antenna at rkm 13.4 installed on 11 March 2010), however there were days when the weir and certain antennas did not function properly.

An individual’s week of immigration, or entry into the study (f_i), was either its capture at the weir or first detection at an antenna (individuals tagged in 2009). The last period (l_i) was either the week of emigration for censored individuals or week 12. I censored individuals recaptured emigrating at the fish weir or displaying distinct, downstream trajectories when the weir did not function properly.
Model Inference

I fit the linear capture-recapture spatial model using a Bayesian framework for analysis. I used the open-source software programs JAGS (Plummer 2003; Plummer 2012) and R (R Development Core Team 2012) via the R package “rjags” (see Appendix B for R code). I ran three chains with an adaptive phase of 10,000 iterations and then evaluated output from an additional 20,000 iterations. I confirmed chain convergence with the potential scale reduction factor (Rhat < 1.01; Gelman and Rubin 1992; Brooks and Gelman 1998). Models required reasonably high computing capabilities (i.e., sufficient random access memory (RAM)) to store all individual activity centers \((s(i,t))\) and alive states \((z(i,t))\).

I decided to use the truncated normal model after comparing parameters (e.g., \(\phi, \sigma, \lambda_0\)) and activity center estimates \((s(i,t))\) between the three models (uniform, normal, truncated normal). The uniform and truncated normal models had very similar parameter estimates (e.g., uniform \(\phi = 0.798, \text{SD} = 0.0119\); truncated normal \(\phi = 0.800, \text{SD} = 0.0119\)) whereas the normal model tended to have higher parameter estimates (e.g., \(\phi = 0.888, \text{SD} = 0.0127\)).

In the uniform model, activity centers \((s)\) were estimated in the middle of the river (e.g., rkm 41) when an individual was not observed in a period. In the normal model, migratory trajectories were smoothed but certain activity centers \((s)\) were in biologically unfeasible locations (i.e., downstream of functioning weir, upstream of impassable dam), especially if unobserved for multiple periods. In the truncated normal model, activity center estimates \((s)\) were biologically feasible even when individuals were unobserved for multiple periods.

Using the truncated normal model results, I evaluated model fit and examined survival, movement and habitat use of American shad in the Little River by comparing
output to other models, descriptive statistics and plots. I compared the linear spatial capture-recapture model weekly survival estimate to a non-spatial version of the same CJS model (Raabe, Chapter 3), where encounter frequencies \( y(i,j,t) \) were reduced to binary \((1 = \text{observed}, 0 = \text{not observed})\) encounter histories still conditional on the alive state \((z; \text{Royle 2008})\). I calculated a weekly population mean location \((\text{rkm})\) from the median estimate of all activity centers \((s(i,t))\) for individuals estimated to be alive and in the river with high certainty \((z = 1)\). For comparison, I computed two weekly population mean locations \((\text{rkm})\) from the empirical observations: 1., all observations combined (sum of each observation \(\text{rkm} / \text{count of all detections}\)), and 2., by individuals (sum of mean \(\text{rkm} \) for each individual / count of detected individuals). To determine if \(\sigma\) functioned properly as a movement parameter, I compared it to the mean range in observations \((\text{rkm})\) for all individuals detected at least twice in a week (Raabe, Chapter 3). I also calculated the mean number of weekly detections per individual as the total number of detections divided by the number of detected individuals to compare to the baseline antenna encounter rate \((\text{antenna } \lambda_{\text{on}})\).

**RESULTS**

The model estimated a mean weekly survival \((\phi)\) of 0.80 (SD = 0.012) for American shad in the Little River in 2010 (Table 4.1), very similar to the non-spatial CJS model weekly estimate of 0.81 (SD = 0.012; Raabe, Chapter 3). This is an estimate of apparent survival due to the possibility of undocumented emigration occurring along with mortalities. I censored 18 individuals recaptured emigrating at the weir and also those with distinct downstream migratory trajectories during periods when the weir did not function properly.
prior to week 12; five others were documented emigrating in week 12. While other tagged fish may have emigrated without being censored, the limited number of censors indicates an overall low seasonal survival rate (23 out of 315 = 0.07). The mean time between the first capture and last recapture/detection (residence time) for all tagged fish was 20.4 days (0.7-88.3, SE = 1.05) or roughly three weeks, equating to an estimated survival of 0.50.

River flow conditions influenced the extent of weekly American shad migrations. The gage height (m) regression coefficient ($\beta_1$) displayed a positive slope in the $\sigma_t$ parameter estimation that informs the model and also provides information on the weekly extent of migrations (upstream and downstream combined; Table 4.1). A positive relationship between river flow conditions and movement was also evident in the weekly mean range in observations of tagged individuals (Figure 4.2). Both the model and empirical metrics depicted American shad undergoing extensive migrations during high flows in week four, were relatively stationary during low flow conditions in the middle of the spawning season, and increased migrations at the end of the spawning period during moderate to high flows. The weekly movement means were more variable because the calculation included fewer fish (individuals with two or more detections) and could be influenced by extreme movements (ranges), whereas the $\sigma_t$ estimates included all fish (any individuals with $z>0$) and is a general regulator of weekly movements for the whole population.

The weekly weir and antenna baseline encounter rates ($\lambda_{0t}$) varied throughout the study period, with the antenna $\lambda_{0t}$’s closely matching the trend in mean detections per individual (Figure 4.3). The estimated weir $\lambda_{0t}$’s were above 0.9 in weeks when the weir functioned properly and large numbers of individuals were captured but were lower when
fewer or no (i.e., week 4) individuals were captured, either due to weir failure or limited migrations (Figures 4.3, 4.4). In the first week, antenna observations were relatively low as individuals were captured at the weir but detected rarely and only at downstream antennas (Figure 4.4). The estimated antenna $\lambda_{ot}$’s were highest in weeks two and three as immigration (weir captures) continued and migrations were partially or completely hindered at the notched dam, resulting in multiple detections at the antenna immediately downstream of the dam (rkm 7.7) and the nearby upstream antenna (rkm 13.4). The $\lambda_{ot}$’s decreased noticeably in week four when higher flows allowed individuals to easily pass the notched dam and spread throughout the river. This reduced multiple detections at antennas near the notched dam and at upstream antennas that were further apart and passed rapidly (e.g., one or two detections). In addition, observations were lower in week four due to high flows that caused the weir to fail (no captures) and reduced antenna efficiencies. The antenna $\lambda_{ot}$’s remained relatively low in weeks five through ten during low flow but experienced an increase in week eleven during freshets. Overall, the antenna $\lambda_{ot}$’s closely followed the trend in mean weekly observations, but were consistently lower because they estimated the expected number of observations for all “alive” individuals (mean $z > 0$) when their activity centers were estimated to be near a sampling location.

The pattern in the weekly mean of individual activity centers generally tracked the means of the observations, but with some deviations (Figure 4.5). The model mean was near the overall and individual means in week one, but slightly higher in weeks two and three. This divergence is likely due to the model estimating the location of undetected individuals during moderately high flow conditions and when detected fish were expected to be detected
more often (high antenna $\lambda_{\text{det}}$ estimates) and migrate (higher $\sigma_t$ estimates); the model was “unaware” of impediment issues downstream of the notched dam (rkm 7.9). The mean activity center estimates are similar to the overall, individual, or both means in the remaining periods. One exception was week nine, when two individuals (of 19 detected individuals) detected often (44% of 54 total detections) at rkm 72.0 heavily influenced the overall mean.

Examining all estimated individual activity centers ($s(i,t)$) depicted the upstream migration of American shad migration, their use of restored habitat following dam removals, and a gradual decline in the number individuals over the spawning season (Figure 4.6). A noticeable upstream shift in activity center locations occurred during increasing flows in weeks two through four and continued in week five. Compared to the distinct upstream migrations from weeks one through five, overall patterns are less distinct in weeks six through twelve as incoming fish tended to migrate upstream while earlier entry fish commenced downstream emigrations. However, the general decline in fish estimated to be alive and in the river ($z > 1$) is more apparent, especially in week twelve. Based on model criteria, all individuals in this analysis passed the downstream complete dam removal (rkm 3.7) and the partial dam removal (rkm 7.9). The model estimated habitat use in reaches restored by complete dam removals at rkm’s 37.7 and rkm 56.4 from weeks two through twelve, including clusters of individuals downstream of the present dam (rkm 82), the upper extent of the model state-space $S$.

Individual American shad displayed a wide range of survival and migratory patterns, characterized well by model activity center estimates but with increased uncertainty in periods of few or no detections and when individuals may have died or emigrated (mean $z <$
Activity center uncertainty (e.g., 95% credible intervals) was much lower when an individual was observed multiple times in a period (e.g., Figure 3.7b, week 3; 23 detections) compared to once (e.g., Figure 4.7b, week 2) or not at all (e.g., Figure 4.7b, week 4). Activity centers tended to move towards the center of the river (e.g., rkm 40) with high uncertainty when the model estimated an individual as not alive / not in the river ($z = 0$) in some but not all model iterations ($0 < \text{mean } z < 1$). A few American shad remained in downstream reaches throughout the spawning period despite being in the river during freshets (Figure 4.7a). A number of American shad were only detected for a short time period at downstream reaches, potentially succumbing to early mortality or using habitat in the long unsampled region between antennas at rkm 13.4 - 45.3 and dying (Figure 4.7b). Other individuals migrated into and used habitat in middle reaches and either successfully emigrated (Figure 4.7c) or died (Figure 4.7d). Movement into upstream reaches was typically rapid during high flow events, with individuals beginning downstream emigration shortly after (Figure 4.7e) or weeks later and completing emigration (Figure 4.7g), while others died in upper reaches (Figure 4.7f) or during emigration (Figure 4.7h).

**DISCUSSION**

The linear spatial capture-recapture model successfully estimated survival and movement of American shad using data collected from a fish weir and linear array of PIT antennas in the Little River. Advances in tagging technology (e.g., low cost PIT tags, continuous monitoring antennas) allowed me to tag hundreds of American shad and passively record thousands of detections. Outside of a 30-minute buffer for consecutive detections, the
model used all collected data and retained the spatial structure of sampling locations. The linear spatial capture-recapture weekly survival estimate was very similar to the non-spatial CJS weekly survival estimate that used the same data as binary encounter histories. The $\sigma_t$ parameter functioned properly as a movement parameter for American shad, representing increased migrations during higher flow conditions. The baseline encounter parameters ($\lambda_{0t}$) also functioned properly, with the weir $\lambda_{0t}$ following trends in captures and the antenna $\lambda_{0t}$ closely tracking the trend in weekly mean detections per individual. Spatially, the individual activity centers visually matched observations and were still estimated in periods without observations, but with higher uncertainty. In addition, the population mean of activity centers were similar to empirical means of observations.

Correlating individual activity centers ($s(i,t)$) to the previous estimate ($s(i,t-1)$) helped maintain migration trajectories. The uniform model estimated activity centers well when individuals were observed in a period but placed individuals near the center of the river when they were not observed, resulting in unrealistic, back-and-forth migratory patterns. A uniform distribution was used in previous studies with a coarser temporal scale (e.g., years instead of weeks) and a focus on home ranges rather than movement patterns (Efford 2004; Royle and Young 2008; Gardner et al. 2010). A model version with activity centers correlated with a normal distribution smoothed migratory patterns, but some activity center estimates were either biologically unlikely (downstream of functioning fish weir, rkm < 0) or impossible (upstream of impassable dam, rkm > 82) and may bias model estimates. For example, survival was estimated higher in the normal model, likely due to individuals located in unsampled regions (i.e., <3.7 rkm and > 77 rkm) where observations were not expected to
occur. In addition, when an individual activity center is estimated in an unsampled location, the subsequent activity center would likely be biased due to correlation between activity centers. The truncated normal distribution for correlating activity centers improved biological realism as all activity centers were contained between the Neuse River (rkm 0) and Atkinson Mill Dam (rkm 82). Activity centers were estimated with relatively high certainty (i.e., 95% small credible intervals) when multiple observations occurred in a period even when spatially spread apart as the model weighted the number of observations at each location and incorporated the weekly movement parameter ($\sigma_i$) and expected number of observations ($\lambda_{0i}$). Activity center estimates still shifted towards the middle of the river when observations did not occur, potentially producing disjointed migratory trajectories. For example, individuals that migrated past the most upstream PIT antenna (rkm 77) and resided in unsampled habitat (rkm 77-82) for multiple periods prior to migrating downstream displayed mean activity center estimates that shifted downstream prior to the true downstream migration period. However, the 95% credible intervals from the linear spatial capture-recapture model accounted for this location uncertainty and in other analyses (e.g., mean location) unobserved individuals are omitted.

Model estimates and the overall spatial resolution could be improved with additional sampling locations ($x(j)$) and increased detection range of continuous monitoring stations. I had only seven sampling locations covering 82 rkm; the minimum spatial gap between locations was 4 rkm and the maximum nearly 32 rkm. Individuals went unobserved for multiple periods, in part due to minimal movement during low flow periods but also because of these spatial gaps. A number of individuals immigrated into the largest spatial gap (rkm
13.4-35.3) and were never observed again. Adding continuous monitoring stations to fill this and other gaps (e.g., downstream of Atkinson Mill Dam) would likely increase observations and decrease unobserved periods, improving estimates of activity centers (and migration patterns) and survival. Ideally, individuals would be constantly observed. Although unrealistic for PIT antennas that require tagged fish to swim through or within the detection range (~1 m; Raabe, Chapter 2), this is a possibility with acoustic telemetry where transmitters can be detected 450 to 600 m from continuous monitoring stations (Simpfendorfer et al. 2008). The main disadvantages of telemetry compared to PIT technology are a lower sample size (transmitter costs) and shorter study periods (transmitter battery life; Lucas and Baras 2000). A constant monitoring of tagged individuals would produce an enormous, valuable dataset that would likely need to be consolidated such as the 30-minute buffer used in this model (Heupel et al. 2006).

A finer temporal scale (e.g. daily) or indicating the temporal sequence of observations may also improve resolution in location, migratory patterns, and relationships with environmental conditions. For example, mean weekly gage height and the movement parameter ($\sigma_t$) may not fully capture a scenario where migrations are minimal during six days of low flow but extensive during the seventh day when a freshet occurs. Because I aggregated weekly observations, the model used the number of observations at each sampling location but did not incorporate when an individual was detected at different locations. Informing the linear spatial capture-recapture model of the temporal sequence of observations could aid in estimating subsequent activity centers (e.g., depict directionality) and the movement parameter as some individuals detected multiple times at multiple antenna

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in a week was due to upstream and downstream migrations rather than consecutive detections.

The linear spatial capture-recapture model had sufficient data despite coarse spatial resolution because American shad are highly mobile species driven to migrate during the spawning season. This mobility presented issues when trying to use a multistate model (Kéry and Schaub 2012) with three reaches (states) in the Little River. A daily time interval was too coarse to assign states as certain individuals were detected in multiple states during high flow events. This led me to develop the linear spatial capture-recapture model that is not restricted to defining a state, instead using all spatial data. However, the model likely would not be applicable for less mobile species unless the spatial resolution is increased (e.g., improved sampling coverage), the temporal scale is longer (e.g., month, year), or active sampling is conducted (e.g., manual tracking, electrofishing).

American shad experienced high spawning mortality, used all habitat restored by dam removals, and migrated more extensively in higher flow conditions in the Little River. The model estimated a weekly survival rate of 0.80, equating to an apparent survival of only 7% after 12 weeks in the river. While this is an apparent survival estimate, it appears spawning mortality is indeed high as documented emigrations events were uncommon in 2010. Mortalities are likely a result of depleted energy reserves (Chittenden 1976; Leggett and Carscadden 1978; Leonard and McCormick 1999), but also could be attributed to predation by invasive flathead catfish whose Little River abundance was highest in 2010 (Raabe, Chapter 3). Similar studies and use of the linear spatial capture-recapture model along the Atlantic coast would provide insight into whether differing iteroparity rates are a result of
spawning or annual (ocean) survival. Starting in week two, tagged American shad occupied habitat throughout the accessible region of the river (rmk 0-82). Upstream migrations were possible due to increased connectivity following one partial and three complete dam removals. American shad migrations were most extensive during a large freshet (week 4) as evident in plots of activity centers and also the highest weekly movement parameter estimate. Burdick and Hightower (2006) documented increased American shad upstream habitat use, especially in a higher flow year, in the Neuse River following removal of an impeding low-head dam (Beasley and Hightower 2000). Similarly, Weaver et al. (2003) saw higher American shad abundance upstream of complete and partial dam removals on the James River, Virginia, during two higher flower years compared to a lower flow year.

The linear spatial capture-recapture model opens new opportunities to study demographic parameters and patterns in movement or migration and habitat use in both aquatic and terrestrial systems. The base model is flexible; parameters may be constant, vary by time, or be a function of environmental or other covariates. Further developments may include heterogeneity in survival, movement, and baseline encounter rates. If the field design includes closely spaced sampling locations (e.g., antenna, acoustic receivers), the model will provide detailed estimates of habitat use and potentially habitat selection. Temporal and spatial overlap and possible interactions between species could be examined by tagging multiple species. The linear spatial capture-recapture model advances quantitative options to analyze continuous monitoring data in a robust manner. Modifications to this model and future quantitative developments are necessary to fully take advantage of tagging technologies that are continuously advancing (Heupel and Webber 2012).
REFERENCES


Table 4.1. Parameter estimates for the 2010 Little River American shad linear spatial CR model. Note: $\phi$ = weekly apparent survival rate, $\tau$ = normal distribution variance for correlation of individual activity centers, $\beta_0$ = regression intercept to estimate $\sigma$, a movement parameter, and $\beta_1$ = regression coefficient for flow (gage height, m) to estimate $\sigma$.

<table>
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<tr>
<th>Parameter</th>
<th>Mean</th>
<th>SD</th>
<th>2.50%</th>
<th>Median</th>
<th>97.50%</th>
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<td>0.78</td>
<td>0.80</td>
<td>0.82</td>
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<td>1.240</td>
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<td>27.03</td>
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<td>2.05</td>
<td>2.09</td>
<td>2.13</td>
</tr>
<tr>
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<td>0.019</td>
<td>0.23</td>
<td>0.26</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 4.1. Map of the Little River, North Carolina, depicting dam locations and status (year removed, notched, present) and fish sampling gear locations in 2010.
Figure 4.2. Weekly sigma ($\sigma_t$), a movement parameter, estimated with a river flow condition covariate (gage height) followed a similar trend as the mean of individual American shad weekly migration distance (range in observations).
Figure 4.3. Weir and antenna baseline encounter rates ($\text{Lam}_0 = \lambda_{0t}$), depicting the expected number of weekly observations when an individual’s activity center ($s_{it}$) was located at a sampling location. Both rates were likely influenced by flow (e.g., weir inundated in week 4) and other factors. The antenna rate closely followed the mean number of weekly observations per individual.
Figure 4.4. Weekly total number of observations (weir captures, antenna detections) for all individuals at each sampling location in the Little River in 2010. Total observations ranged from 1 to 714 detections, and bubble sizes are relative to the highest number of observations (714, week 3, rkm 7.7).
Figure 4.5. Estimated weekly mean location of the American shad population in the Little River during the spring of 2010 based on the linear spatial capture-recapture model (estimated individual activity centers) and observations (overall = sum of rkm / count of observed individuals, individual = sum of mean rkm for each individual / count of observed individuals).
Figure 4.6. Top. Individual activity center (s) estimates for each American shad in the Little River estimated to be alive with high certainty (mean $z = 1$) relative to weekly mean water depth and former and current dam sites (large dash: removed, small dash: partially removed, solid: present) (note: s’s randomly offset from time period for visual purposes). Bottom. Weekly number of American shad that immigrated, emigrated, and were estimated alive (mean $z = 1$).
Figure 4.7. Examples of American shad migratory and survival patterns in the Little River. Individual activity centers (filled circle, solid line, weekly midpoint, 95% credible intervals, CI) were predicted from weekly observations (open circle, dashed line, continuous time). Different CI lines represent probability (mean $z$) individual is alive and in the river: black, solid ($z=1$), grey, small dashed ($z=0.1-0.5$), light grey, large dashed ($z<0.1$).
CHAPTER 5
Conclusion

Based on the results of these studies, I conclude that dam removals benefit migratory fishes. While this study lacked pre-removal data or a control river, Collier and Odom (1989) noted the two most downstream dams (rkm 3.7, 7.9) were potentially passable under high flow conditions while Rains Mill Dam (rkm 37.7) was impassable under all flow conditions. Numerous species were captured migrating in both directions at the two fish Little River weir locations (rkm 56.4 in 2007, rkm 3.7 in 2008-2010); the dams previously present at these sites likely precluded or at least delayed movement between adjacent reaches. River-wide, dam removals increased connectivity between reaches and allowed migratory species access to different habitats of their preference for spawning, foraging, and refuge. American shad *Alosa sapidissima* and gizzard shad *Dorosoma cepedianum* used upstream habitats and were documented downstream of Atkinson Mill Dam (rkm 82.3). Higher habitat complexity, especially in terms of substrates, occurred upstream of rkm 13.4. Therefore, American shad could find suitable spawning habitat throughout most of the river (Hightower et al. 2012). Potential disadvantages of dam removal include upstream migrations of introduced species and spread of diseases (Lejon et al. 2009; Hurst et al. 2012). In the Little River, few introduced catfishes (Ictaluridae) including flathead catfish *Pylodictis olivaris* were captured at the weir in 2007 (rkm 56.4) and detected at antennas in middle and upstream reaches in 2009 and 2010. Fewer large predators in the most upstream reaches suggests those locations may also serve as refuge for adult and young fish.
I found that fish migrations were likely impeded or delayed at the City of Goldsboro notched dam (rkm 7.9). Gizzard shad required the deepest water to pass, followed by American shad, whereas water depth did not appear to influence passage by flathead catfish. Potential impediments and delays are of the greatest concern for American shad as wasted energy expenditures may limit their upstream migrations to more suitable habitat while increasing mortality due to physical exhaustion and starvation (Castro-Santos and Letcher 2010). Concentrations of individuals below the dam also may increase vulnerability to flathead catfish predation. The partial dam removal is undoubtedly an improvement over the intact dam but further improvements in fish passage appear possible based on my results.

Increased abundance is the primary goal of dam removal and fish restoration efforts (Doyle et al. 2003). American shad captures and estimated populations increased from 2007 to 2009, but decreased in 2010. The lower 2010 abundance may be a real trend but also could be a result of natural variability, the estimation method (sensitive to downstream captures), or higher flathead catfish predation. A follow-up study after multiple generations of American shad have had an opportunity to use habitat restored by dam removals would be extremely beneficial (Hasselman and Limburg 2012). Similarly, comparing other species abundance in a follow-up study would provide further evidence to evaluate dam removal success and also the influence of flathead catfish on the Little River fish community.

While this study greatly increased knowledge of migratory fishes responses to dam removals, further dam removal evaluations with improved study designs are still needed. This study lacked pre-removal information on migrations and abundance, instead relying on Collier and Odom’s (1989) conclusions from a literature review and interviews. Past studies...
with pre- and post-removal data have shown increased upstream migrations and spawning in restored habitat (e.g., Weaver et al. 2003; Burdick and Hightower 2006). As many smaller dams, but also a few larger dam removals are planned, I recommend long-term studies (e.g., multiple generational time) with pre- and post-dam removal data to fully allow potential benefits of access to restored habitat to occur. Furthermore, if possible, concurrent studies on one or multiple rivers with similar attributes (e.g., geography, hydrology, size, species composition) may allow researchers to determine whether changes in connectivity, habitat use, and abundance are a result of dam removals or temporal and environmental variation. Incorporating long-term tags to evaluate actual differences in individual migrations pre- and post-removal would also be beneficial.

Flow conditions proved to be the driving factor in fish migrations during the spring in the Little River, while water temperature appeared important for immigration and emigration periods. Weir captures and antenna detections increased during freshets, as did the extent and speed of migrations. Increased flow likely provides an opportunity to pass natural and anthropogenic (i.e., notched dam) migratory obstructions and higher turbidity may decrease predation vulnerability and offer a window to migrate freely (Jonsson 1991). Fish may also migrate during increased flow because conditions are no longer suitable at their current location. Therefore in a given year, the timing, duration, and number of increased flow events may strongly influence the use of restored habitat and potentially reproductive productivity if upstream spawning or nursery habitat is of higher quality. Increased flow can also enhance downstream migrations (Jonsson 1991). American shad downstream migrations were rapid during freshets, potentially aiding in survival and iteroparity rates.
Given the strong influence of flow conditions in the Little River, I recommend additional studies in tributary and mainstem rivers, including regulated rivers where flow is controlled by upstream dams. Experimentally determining response mechanisms, migratory expenses, and reproductive success under different flow conditions would be extremely informative.

I have provided the first known information on migrations of gizzard shad, certain redhorses *Moxostoma sp.*, and expanded on a few previous catfish studies in their introduced range (Pine 2003; Malindzak 2006). Gizzard shad used upstream restored habitat the most extensively of all migratory species, with some individuals migrating the entire river multiple times in the spring; these migrations were unlikely to occur when the dams were present. Gizzard shad are an important forage species in lakes, reservoirs, rivers, and estuaries (Overton et al. 2009), but their role in rivers has received limited study. Further study of the purpose (e.g., spawning, foraging, refuge) for their extensive migrations and their role in riverine ecosystems would be beneficial. Notchlip redhorse *Moxostoma collapsum* and shorthead redhorse *Moxostoma macrolepidotum* may reside in the Little River year-round as few individuals were captured immigrating at the downstream weir site (rkm 3.7). Redhorses influence ecosystems through foraging, nutrient cycling, transporting mussel glochidia, and have high biomass that can be prey for fish and terrestrial species (Cooke et al. 2005). Migrations of both redhorse species were not extensive, potentially due to their preferred spawning (e.g., gravel, cobble) and foraging habitat located throughout the river. The cause and population influence of noticeable notchlip redhorse spawning mortalities in 2007 warrants further study. Flathead catfish and channel catfish *Ictalurus punctatus* displayed similar migratory distributions, with some individuals migrating into the uppermost reach but
many remaining in lower and middle reaches. Blue catfish *Ictalurus furcatus* were less abundant and remained in lower reaches. Many flathead catfish emigrated in June, but I did not observe emigrations of the other two species. All three species are introduced in North Carolina and will consume fish, but flathead catfish are obligate carnivores. Flathead catfish and blue catfish commonly attain sizes capable of consuming adult American shad while only the largest channel catfish may be capable of consuming adults.

Even though American shad have been studied extensively, I provided substantial new information regarding their spawning biology. Telemetry studies have documented migrations and spawning habitat locations, but this study is the first to tag and monitor thousands of individuals and also to document individuals returning in a subsequent year to a North Carolina river. A disadvantage of using PIT technology with low detection range was that I did not locate preferred spawning locations. In future PIT studies, increasing the number of antennas and further exploring portable antennas could potentially locate spawning habitat. The extent and transition rates of American shad migrations were heavily influenced by flow conditions. In turn, use of upstream habitat was highest for individuals that immigrated during or shortly before a freshet event and may factor into annual reproductive success. Most American shad emigrated after water temperatures were consistently above 20 °C, presumably after spawning in their preferred temperature range (Walburg and Nichols 1967; Hightower et al. 2012). While studies have examined weight loss and energy use in rivers (Leggett 1972; Chittenden 1976; Glebe and Leggett 1981; Leonard and McCormick 1999), I was the first to examine the proportion of weight lost by recaptured individuals and found that duration of residence combined with water temperature
was a strong predictor; distance traveled displayed a positive but weaker relationship. For recaptured individuals and individuals only captured immigrating or emigrating, males lost a noticeably smaller proportion of their initial weight than females, contradicting previous studies using groups of individuals at different time periods (Leggett 1972; Chittenden 1976).

I also provided the first within season spawning survival rates (0.07 to 0.17), indicating high spawning mortality occurs in the Little River. However, no distinct factors (e.g., sex, size, distance traveled) influencing spawning survival were documented.

I also provided the first estimates of the potential biomass consumed by a population of introduced flathead catfish, focusing on the number of American shad consumed along with the spatial and temporal overlap of these two species. Flathead catfish maximum consumption was estimated to be 7-36% of the estimated Little River population of American shad in 2010. While I assumed that flathead catfish consumed only American shad, I believe the estimates are plausible because American shad were the most abundant prey and the estimates may even be low. For example, I divided the consumed biomass by median American shad size, but flathead catfish may target smaller individuals. My flathead catfish consumption estimates were based on Bourret et al.’s (2008) juvenile laboratory study, Slaughter and Jacobson’s (2008) equation for gape width, and my estimates of American shad body depth from preserved specimens. Using flathead catfish individuals from their introduced range, I encourage laboratory studies of adult consumption rates and gape widths capable of consuming varying sizes of adult American shad. In the Little River, a large proportion of the 2010 flathead catfish population was estimated to be slightly below or at the size capable of consuming only the smallest American shad. Growth after 2010 will
gradually but substantially increase the biomass of flathead catfish large enough to consume American shad, raising further concerns on their influence towards American shad restoration efforts.

The concern of flathead catfish predation influencing American shad restoration efforts appears warranted. Mitigation efforts should focus on reducing both abundance and the size structure of flathead catfish populations so fewer individuals are capable of consuming adult American shad. Pine et al. (2007) estimated that sustained, annual removal (6-25%) of flathead catfish could noticeably reduce their impact on native fish communities. In North Carolina, no creel limits exist for flathead catfish as they are not considered a game fish. Encouraging harvest by recreational anglers, developing a commercial fishery, and concerted removal efforts will not eradicate flathead catfish but could reduce their overall influence. The potential positive for American shad from my research is that many individuals entering in March and April and those migrating into upstream reaches likely had the opportunity to spawn. In March and April, when consumption rates were estimated to be lower due to low water temperatures (Bourret et al. 1998), fewer flathead catfish were in the river and remained in lower reaches. If flathead catfish predation is a driving factor, it is possible that American shad spawning runs will gradually shift to earlier in the spring.

Telemetry technology continues to advance rapidly (Heupel et al. 2006), and my linear spatial capture-recapture model provides a new tool to estimate both demographic and spatial parameters from large datasets. Telemetry data are often examined with descriptive statistics, plots, and maps useful for summarizing habitat use, distributions, migrations, and fish passage rates but with limited statistical analysis. My initial attempts to use a multistate
model to estimate American shad apparent survival and transition (migration) probabilities into three different Little River states (i.e., reaches) was unsuccessful due to the extensive migrations into multiple reaches, even at a daily time period. This led me to develop the linear spatial capture-recapture model that is not restricted to a limited number of states, instead using all spatial data within a time period to estimate both demographic and spatial parameters. I developed the model by modifying terrestrial two-dimensional models (e.g., Gardner et al. 2010). By accounting for the autocorrelation in activity centers, I was able to estimate the location of individuals even when they were not detected in a time period. Missed detections and periods when the weir or a PIT antenna failed were incorporated into baseline detection parameters. The movement parameter informed the model of the extent of individual migrations in a time period, and by using a flow condition (gage height) covariate I was able to examine the relationship between weekly movement and river conditions. I recommend using the linear spatial capture-recapture model for American shad and other species in multiple systems to compare survival and movement rates. In addition to rivers, the model is applicable to a variety of aquatic and terrestrial linear arrays including lake shorelines, migratory routes, and corridors. The linear spatial capture-recapture model opens new opportunities to study demographic parameters, movement and migration patterns, species temporal and spatial overlap, and habitat use.

Finally, I conclude that the resistance board fish weir combined with PIT technology is an extremely effective method to capture, tag, and monitor migratory fishes but systems the size of the Little River are at the upper extent of both gear’s functionality. Both gears were reliable in low to moderate flows, but had issues in higher flows including flood events.
This is undesirable, especially considering higher activity of migratory fishes during these periods. The fish weir required considerable effort to construct, install, and remove. However, it was very effective in capturing fish compared to electrofishing in the Little River. It also provided a fixed location to monitor immigrations and emigrations. Mortality did occur at the weir, primarily for American shad that are sensitive to handling regardless of capture method (Hendricks 2003). My modification to the resistance board weir included a floating downstream cage that improved capture and reduced incidental mortality. Antennas were much easier to install than the fish weir, but still more challenging and vulnerable to flow conditions than stationary telemetry receivers. Narrower antennas at upstream locations had greater read ranges and functioned better during high flow events than downstream antennas. Rotating the antennas so all cables are installed along the bottom (“flat-plate”) reduces drag and boater interference, but at the cost of reduced detection probabilities. My antennas were able to cover over a meter of water depth, sufficient during low to moderate flows but may have missed individuals swimming above or along the banks during higher flows. The long-term PIT tags (no batteries) allowed me to document returning American shad and monitor resident species in subsequent years that were detected but not recaptured. Multiple years of tagging long-lived species results in a large population of tagged individuals that can be monitored in future years with limited or no handling stress or mortality, providing healthy individuals and natural migrations (Hewitt et al. 2010). Overall, the weir and PIT antennas successfully monitored migrations and provided valuable encounter histories used in the linear spatial capture-recapture model.
REFERENCES


APPENDICES
APPENDIX A. Supplementary figures and photographs.

Figure A.1. Two views of a partially removed (notched) dam on the Little River with a concrete rubble spillway and PIT antenna installed across the structure. The dam is located at the City of Goldsboro water treatment plant (rkm 8).
Figure A.2. Aerial and cross-sectional views (top) of weir components in 2009-2010 that spanned the Little River immediately downstream of the former Cherry Hospital Dam. Installed fish weir (bottom, March 15, 2008), with resistance board weir and white bulkheads in center, upstream live cage to the left and picket weir sections on both sides. The downstream live cage was installed on the third from left resistance board weir panel.
Figure A.3. Modification of a resistance board panel (top) to create a distinct flow into an attached floating cage (bottom) to funnel and capture fish migrating downstream in the Little River.
Figure A.4. Diagram (top) and photograph (bottom) of PIT antenna components. The Texas Instruments Series 2000 reader consisted of a control module (RI-CTL-MB2) and a remote antenna radio frequency module (RI-RFM-008) and resonance tuner box (RI-ACC-008). Data were stored on an Oregon RFID datalogger.
Figure A.5. Examples of PIT antennas installed on the Little River: multiplex antenna downstream of the notched dam (top, rkm 7.7), former Lowell Mill Dam (bottom left, rkm 56.4), and Shoeheel Road (bottom right, rkm 72.0).
Figure A.6. Notchlip redhorse collected at fish weir on April 23, 2007, with damage to caudal peduncle and fin.
Figure A.7. Two examples of flathead catfish predation on American shad in the Little River in 2009: an American shad tail protruding from flathead catfish gullet (top) and an American shad PIT tag removed from the stomach of a dead flathead catfish (bottom).
Figure A.8. Example of a spent, emaciated female American shad. Individual (468 mm, 506 g) was found dead on the fish weir panels (migrating downstream) on May 19, 2010.

Figure A.9. Dead male American shad recovered immediately downstream of Atkinson Mill Dam on May 13, 2010. Individual was tagged migrating upstream at the fish weir on March 15, 2010, and last detected migrating upstream at rkm 77.0 on March 30, 2010.
APPENDIX B. Program R code for linear spatial capture-recapture model.

# Code for spatial linear capture-recapture model used for 2010 American shad in the Little River, NC

setwd("file path")
library(rjags)
library(reshape)

# Constants:
M <- 315  # Number of individuals
T <- 12   # Number of periods (weeks)
nantenna <- 7  # Weir, 6 antennas
antenna.loc <- c(3.7, 7.7, 13.4, 45.3, 56.4, 72.0, 77.0)  # Sampling locations
xl <- 0  # Lower boundary, river mouth
xu <- 82  # Upper boundary, Atkinson Mill Dam

# Input and format data matrix:
# y = detection history (individual (i) x antenna (j) x week(t)); first = river immigration week, last = river
# emigration week, flow1 = mean weekly gage height, flow = standardized gage height, ON = proportion of
# sampling gear functioned ### Note: R package reshape (commands melt and cast) used to organize y data

sink("filename.txt")
cat(""

textfile specification

model { #model

# Priors
phi ~ dunif(0,1)  # Survival (constant)
mu ~ dunif(-3,3)  # Intercept in sigma estimate
beta ~ dunif(-3,3)  # Coefficient for flow in sigma estimate
tauv ~ dunif(0,40)  # Normal dist spread for correlated S's, delete for uniform model
tau <- 1/(tauv*tauv)  # Normal dist spread for correlated S's, delete for uniform model

for (t in 1:T){
    log(sigma[t]) <- mu + beta * flow[t]  # Weekly sigma, flow covariate
    sigma2[t] <- sigma[t] * sigma[t]  # Weekly sigma2
    # w_lam0[t] ~ dunif(0, 1)  # Weekly weir encounter rate
    lam0[t] ~ dgamma(0.1, 0.1)  # Weekly antenna encounter rate
}

for (t in 1:3){
    w_lam0[t] ~ dunif(0, 1)  # Weekly weir encounter rate
}

}
for (t in 4) {  #t
  w_lam0[t] <- 0  # Weir did not function entire week 4, set to 0
}
for (t in 5:12) {  #t
  w_lam0[t] ~ dunif(0, 1)  # Weekly weir encounter rate
}

for (i in 1:M) {  #m
  for (t in 1:(first[i]-1)) {  #t
    S[i,t] <- 0  # Individual not in river, needed to follow node in JAGS
    z[i,t] <- 0  # Individual not in river, needed to follow node in JAGS
  }
  # Individual’s first period
  z[i,first[i]] ~ dbern(1)  # Individual known to be alive at entry into study area
  S[i,first[i]] ~ dunif(0,82)  # No prior information on individual’s location
  # First period, weir
  D2[i,1,first[i]] <- pow(S[i,first[i]]-antenna.loc[1], 2)  # Estimate activity center
  w_lam[i,1,first[i]] <- (1-exp(-w_lam0[first[i]]))/exp(-D2[i,1,first[i]]/(2*sigma2[first[i]]))  # Lam0,sigma
  tmp[i,1,first[i]] <- w_lam[i,1,first[i]]*ON[1,first[i]]  # z = 1 on entry, encounters, gear functioning
  y[i,1,first[i]] ~ dbern(tmp[i,1,first[i]])  # Fit Poisson model
  # First period, antennas
  for(j in 2:nantenna) {  #j
    D2[i,j,first[i]] <- pow(S[i,first[i]]-antenna.loc[j], 2)
    lam[i,j,first[i]] <- lam0[first[i]]/(2*sigma2[first[i]])
    tmp[i,j,first[i]] <- lam[i,j,first[i]]*ON[j,first[i]]
    y[i,j,first[i]] ~ dpois(tmp[i,j,first[i]])
  }
  # Subsequent periods
  for (t in (first[i]+1):last[i]) {  #t
    # S[i,t] ~ dunif(0,82)  # uniform, no correlation
    # S[i,t] ~ dnorm(S[i,t-1], tau) # normal, correlated S
    S[i,t] ~ dnorm(S[i,t-1], tau)*T(0,82) # truncated normal, correlated S
    D2[i,1,t] <- pow(S[i,t]-antenna.loc[1], 2)
    w_lam[i,1,t] <- (1-exp(-w_lam0[t]))/exp(-D2[i,1,t]/(2*sigma2[t]))
    tmp[i,1,t] <- z[i,t]*w_lam[i,1,t]*ON[1,t]
    y[i,1,t] ~ dbern(tmp[i,1,t])
  }
  for(j in 2:nantenna) {  #j
    D2[i,j,t] <- pow(S[i,t]-antenna.loc[j], 2)
    lam[i,j,t] <- lam0[t]/(2*sigma2[t])
    tmp[i,j,t] <- z[i,t]*lam[i,j,t]*ON[j,t]
    y[i,j,t] ~ dpois(tmp[i,j,t])
  }
  phiUP[i,t] <- z[i,t-1]*phi  # Estimate overall weekly survival rate
  z[i,t] ~ dbern(phiUP[i,t])  # Estimate individual alive state
}

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# Periods after censor
for(t in (last[i]+1):T) {#t
    S[i,t] <- 0 # Fish no longer in river, needed to follow node in JAGS
    z[i,t] <- 0 # Fish no longer in river, needed to follow no node in JAGS
} #t
} #m
} #model

##correct fish that "misbehave" and encounter weir more than once
y[107,1,3] <- 1
y[260,1,1] <- 1

#Set up a data input
data1 <- list(y=y, first=first, last=last, flow=flow, M=M, ON=ON, T=T, nantenna=nantenna, antenna.loc=antenna.loc)

z <- matrix(NA, M, T) # Aids in initialization
for(i in 1:M){ # M
    for(t in first[i]:last[i]){ # T
        z[i,t] <- 1
    } # T
} # M

w_lam0 <- c(0.75, 0.25, 0.5, 0, 0.75, 0.5, 0.25, 0.5, 0.25, 0.75, 0.25, 0.5) # Needed to force week 4 to 0

#Set initial values
inits = function() {list(z=z, phi=runif(1,0,1), w_lam0=w_lam0, lam0=runif(12,1,3), tauv=runif(1,0,30), mu=runif(1,1,3), beta=runif(1,0,1))}

# Parameters to follow
parameters <- c("sigma", "phi", "w_lam0", "lam0", "mu", "beta", "tauv", "S", "z")
# NOTE: following S and z requires large amount of RAM

out1 <- jags.model("filename.txt", data1, inits, n.chains=3, n.adapt=10000)
out2 <- coda.samples(out1,parameters,n.iter=20000)

# gelman.diag(out2[,1:31]) # Test of chain convergence
# gelman.diag(out2[,33:40])

# sink("filename_results.txt") # One option to save output
# summary(out2)
# sink()

# dput(out2, "LR_AS_SpatialCR_TruncatedWeirL_out2") # Save everything