Abstract

SMITH, JOSEPH ALAN**.** Spawning Activity and Migratory Characteristics of American Shad and Striped Bass in the Cape Fear River, North Carolina. (Under the direction of Joseph E. Hightower.)

Anadromous fish populations within the Cape Fear River, North Carolina have experienced declines since the late 1800s. Three low-head lock and dam structures contributed to this decline by limiting access to upstream habitat. I used egg sampling and sonic telemetry to characterize patterns of migration and spawning activity for American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*). Plankton samples were collected below each lock and dam, and at two locations farther upstream. Distribution and stage of development of American shad eggs, as well as observed spawning activity, suggest that most American shad spawning took place downstream of the lowermost lock and dam [river km (rkm) 97]. Egg density decreased by an estimated 90% with each successive dam moving upstream. In 2007, 20 American shad and 20 striped bass were captured and transported to a release location upstream of the three locks and dams, where they were tagged with sonic transmitters and released. Sixty percent of American shad in 2007 moved 1 to 33 rkm upstream of the release site, at an average migration rate of 2.30 rkm/hr. All striped bass tagged in 2007 moved downstream upon release. However, two striped bass made secondary upstream migrations of 52 and 134 rkm, through two and three dams, respectively, and at an average rate of 2.58 rkm/hr. In 2008, 20 American shad and 20 striped bass were captured, tagged with sonic transmitters, and released at

their capture locations (all but two striped bass downstream of the first lock and dam). Sixty-five percent of American shad and 77% of striped bass made upstream movements past the lowermost lock and dam in 2008, with average migration rates of 3.2 rkm/hr for American shad and 3.0 rkm/hr for striped bass. Furthermore, 35% of American shad and 25% of striped bass that made upstream movements were able to migrate upstream of the uppermost lock and dam (rkm 186). Based on passage rates at the three locks and dams, American shad would be expected to be most abundant downstream of Lock and Dam 1 (where egg collections were highest) and upstream of Lock and Dam 3. For striped bass, the section of the river between Lock and Dams 2 (rkm 149) and 3 (rkm 186) had the highest egg collections and highest predicted proportion of the run. In combination, these results demonstrate that the locking program provides some access to historical spawning habitat, although further improvements in fish passage could benefit both species.

Spawning Activity and Migratory Characteristics of American Shad and Striped Bass in the Cape Fear River, North Carolina

by
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Biography

My homeland is the great "volunteer" state of Tennessee, specifically, a small city in the Ridge and Valley Physiographic Province of upper east Tennessee called Kingsport. As a child, I was very fortunate to live at the base of Bays Mountain Park and State Natural Area, which lies along the crest and inside slopes of Holston River Mountain and Bays Mountain. The forests and waters of that land were ecological playgrounds and are the origins of my interest in the world of natural resources. I spent countless hours wading through creeks flipping rocks for "crawdads" and "grampus" and hauling my seine made from an old window screen in pursuit of "minnows". I took advantage of every chance I had to fish for bass and bluegill in the small reservoir that was the centerpiece of the park's watershed. Needless to say, my "fishing fever" was contracted right in my own backyard.

Although the majority of my free time was spent fishing the ponds, creeks, rivers, and reservoirs of my home state, the idea of a career conserving such valuable resources did not arise until many years after high school. My true appreciation for aquatic resource management began with volunteer work at the Tennessee Valley Authority (TVA) in Knoxville, Tennessee, where I worked with biologists sampling aquatic organisms and habitat of small streams and rivers in the Tennessee River watershed. This experience opened my eyes to new possibilities and led to my decision to return to college.

While pursuing my education, I continued to volunteer and subsequently work as a contract biologist for TVA. I graduated from Pellissippi State Technical Community

College with an Associate of Science degree and immediately transferred to the University of Tennessee (UTK), where I obtained a Bachelor of Science in wildlife and fisheries science. While at UTK, I was employed as a field technician, worked with graduate students on various fisheries projects, and took part in volunteer activities as part of a student fisheries group.

After graduation from UTK, I obtained a position as a Natural Resource Biologist with the Maryland Department of Natural Resources (MDNR). While at MDNR, I was part of the Monitoring and Non-Tidal Assessment group, which was responsible for tracking the status of the state's low-order streams. Although appreciative of the experience in Maryland, I was eager for the opportunity to obtain a Master of Science in aquatic resource management. So when I saw an opening available at North Carolina State University to work with Dr. Joe Hightower on unique species, in a large coastal river system, I jumped at the chance. Since my fortunate acceptance to the project, I have been given outstanding guidance, support and encouragement. I hope to use the knowledge and skills from all my experiences to protect and conserve the priceless natural resources that have given so much to me throughout my life.

Acknowledgments

I give great thanks to my committee chair Dr. Joseph E. Hightower for giving me the opportunity to work under his direction. I have gained much respect and admiration for him over the years and I have benefited greatly from his guidance. I also thank my committee members; Kevin Gross for volunteering his time and effort to assist me with critical data analysis and Tom Kwak for also volunteering his time and providing me with valuable input.

I thank United States Army Corps of Engineers personnel Frank Yelverton, Carol Banaitis, and Craig Shoe for funding and logistical support, as well as lockmasters Robin Hall and Phil Edge for their time and assistance. I also give great appreciation to North Carolina Wildlife Resources Commission (NCWRC) biologists Keith Ashley and Tom Rachels for their valuable time and effort collecting and transporting fish for tagging, Jeff Evans and staff at the NCWRC Watha Hatchery, and the staff at the Pechmann Fishing Eduction Center.

I especially thank field technicians McLean Seward and Matt Lubejko for putting in all the hours of hard work through rainy days and bug infested nights, as well as for being outstanding living and working partners in the quest for Cape Fear knowledge. I also appreciate access to the river provided by landowners David “Poke” Hurley, Randy Joyner and the late Sol Rose. Great appreciation is also given to my fellow graduate students for their assistance and moral support over the years. Last, but definitely not least, I thank my mom for always being my best supporter in all of my life’s endeavors.

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Introduction

Anadromous fish species (those that live primarily in saltwater and migrate into freshwater to spawn) have long been an important resource along the Atlantic coast of the United States. These fish depend on coastal freshwater systems to provide spawning and nursery habitat for their unique life history strategy. The success of these species depends on their ability to reach suitable spawning habitat that is often hundreds of kilometers upriver from the sea. Dams are obviously a major factor affecting these populations. They alter downstream habitat, block migration to upstream spawning areas, and limit the availability of nursery habitat for progeny (Beasley and Hightower 2000; Burdick and Hightower 2006). The loss of habitat can be substantial; for example, Collier and Odum (1989) reported that American shad lost 350 km of habitat in the main stem and tributaries of the Roanoke River due to construction of dams. Patrick (2006) hypothesized that dams force anadromous fishes to spawn in marginalized habitats that lessen reproductive success and recruitment.

There are about 2,000,000 dams less than 14 m tall in the United States (Collier et al. 1996; Poff and Hart 2002). Only a small number are removed annually due to factors including dam age and negative environmental impacts (Shuman 1995). However, the cost of dam removal is often prohibitive (Born et al. 1998; Smith et al. 2000), so different methods of upstream passage have been implemented in lieu of dam removal. These methods include the construction of fishways and fish ladders or the operation of fish lifts

(Weaver et al. 2003; Sprankle 2005). In the Savannah River, Georgia/South Carolina, navigation locks are utilized to promote upriver passage of anadromous fish through a low-head lock and dam (Bailey et al. 2004). This scenario is similar to that currently faced by anadromous fishes migrating in the Cape Fear River, North Carolina.

The Cape Fear River historically supported large runs of anadromous species, but population levels have declined substantially over the last two centuries (Rulifson 1994; Winslow 1994). The most important species historically, in terms of commercial and recreational fishing, were sturgeon *Acipenser spp.,* American shad *Alosa sapidissima* and striped bass *Morone saxatilis*. Sturgeon dominated the fishery of the late 1800s (McDonald 1887) but only a small population of Atlantic sturgeon *A. oxyrinchus* and very small number of shortnose sturgeon *A. brevirostrum* persist today (Winslow et al. 1983; Moser and Ross 1995). At the turn of the 20th century, this was one of the most productive rivers for American shad in North Carolina (Nichols and Lounder 1970). Estimated commercial landings within the Cape Fear River system in 1896 totaled 144,072 kg, of which the Cape Fear River produced 76%, the Northeast Cape Fear River 15%, and the Black River 9% (Stevenson 1899). In 1904, Cobb (1906) reported basinwide landings of 140,398 kg, with the Cape Fear River again accounting for the majority (77%) of the catch. However, the average commercial landing of American shad in the Cape Fear River system fell from over 136, 080 kg in 1896 and 1904, to 80,287 kg from 1957 to 1965 (Nichols and Louder 1970). The commercial harvest of American shad in 2005 on the Cape Fear River was only 7,852 kg (ASMFC 2007).

The American shad fishery of the 1800s also included annual incidental catches of striped bass of about 545 kg. In comparison to other North Carolina coastal river systems, however**,** the striped bass fishery in the Cape Fear River system has traditionally been small (Ashley and Rachels 2007). Currently, the Cape Fear River striped bass population is among the lowest of North Carolina's coastal rivers (McDonald 1887; Patrick and Moser 2001; Ashley and Rachels 2007). In 2008, the North Carolina Division of Marine Fisheries (NCDMF) and North Carolina Wildlife Resources Commission (NCWRC) implemented a complete harvest moratorium on striped bass in the Cape Fear River system for both the recreational and commercial sectors in an attempt to promote recovery of the fishery (NCDMF 2008; NCWRC 2008).

Declines in anadromous species landings in the Cape Fear River have been attributed to the same variety of anthropogenic effects (overfishing, pollution, habitat degridation, dam construction) that have impacted many other Atlantic coastal rivers (Winslow et al. 1983; Winslow 1994). However, the most obvious of these effects in the Cape Fear River is the presence of three low-head lock and dam structures, approximately 4 m tall, constructed between 1915 and 1934 by the United States Army Corps of Engineers (USACOE) for the purpose of commercial navigation. Lock and Dam 1 (LD-1) was constructed at river kilometer (rkm) 97 in 1915, Lock and Dam 2 (LD-2) at rkm 149 in 1917, and Lock and Dam 3 (LD-3) at rkm 186 in 1934 (Nichols and Louder 1970).

These obstructions were not the first to impact anadromous fish migration in the Cape Fear River. A map from 1852 shows the presence of many lock and dam structures

along the Cape Fear River upstream of Fayetteville, North Carolina (Thompson 1852). These early structures were built to aid ships transporting coal from the Deep River Coal Company. located along the shores of the lower portion of the Deep River. However, disrepair of these locks and dams after destructive flooding around the time of the Civil War rendered them ineffective (NCDCR 2008). Shortly after this period, Stevenson (1899) reported no artificial barriers to migration in the Cape Fear River and found American shad migrating upstream to Smiley Falls (rkm 261). Similarly in 1904, American shad were found 224 kilometers upstream near Fayetteville, North Carolina, and spawning occurred from the mouth of the Black River to Fayetteville (Cobb 1906). However, the construction of the locks and dams prevented such upstream passage, except during boat lockage and possibly during extended periods of high flow (Nichols and Louder 1970). Although fish ladders were constructed at each of the three locks and dams, anadromous fish were shown to be unsuccessful at utilizing them (Davis and Cheek 1967; Nichols and Louder 1970).

In 1962, a program was implemented through an agreement among the NCWRC, USACOE, and United States Fish and Wildlife Service (USFWS) to use the lock at each dam to move fish upstream to continue their spawning run (Fischer 1980; Moser et al. 2000). Nichols and Louder (1970) evaluated the use of the locks for anadromous fish passage from 1962 to 1966. They estimated that 9,770 American shad passed through LD-1, 1,110 at LD-2, and 50 at LD-3. Moser et. al. (2000) estimated that passage efficiency rates for American shad at LD-1 were 18-61% over a three-year period, with higher rates

resulting from changes in lockage frequency, length of operating season, gate arrangement and attractant flow. Additional telemetry studies from 2003 to 2004 (when 10 or more individuals with transmitters reached LD-1) found passage rates were 26-33% for American shad and 23-61% for striped bass (CZR 2004). Currently, the USACOE conducts fish lockages at each dam three times per day, from March to June and once each day throughout the remainder of the year, under normal flow conditions (R. Hall, USACOE, personal communication). The procedure entails opening one side of the lower gate of the lock for an extended period of time while valves within the upstream gate are opened to create an attractant flow. The lower gate is then closed and the water level inside the chamber is raised to that of the upstream pool. The upper gate is then opened to allow fish to move upstream (Moser et. al. 2000; R. Hall, USACOE, personal communication).

Although the findings of previous researchers on the Cape Fear River indicate some upstream passage of American shad via the lock chambers, they also illustrate that there remains a substantial proportion of fish that do not access upstream spawning areas. That problem has prompted new discussion about ways to further improve anadromous fish passage on the Cape Fear River. The goal of this research was to characterize the current patterns of migration and spawning activity for American shad and striped bass in the Cape Fear River and to examine the potential effect of the locks and dams on fish passage and spawning distribution. Tracking the movements of these fish, along with conducting egg and larval fish surveys, will help to identify areas of concentrated

spawning activity, uncover patterns and preferences in habitat characteristics, and further assess the impact of the three dams on fish distribution. Ultimately, the new findings provided by this study will serve to aid in present and future management decisions regarding the recovery of this important resource.

Reproductive Biology

American shad

Male American shad reach sexual maturity between three and five years old, while females mature between four and six years old (Leim 1924). Egg development in females occurs between 13°C and 17°C, and increases in rate from 17°C to 20°C (Walburg and Nichols 1967). Fecundity (58,000 to 660,000 eggs per female) is highly variable among populations of American shad (Cheek 1968; Jones et al. 1978; Leggett and Carscadden 1978). Studies suggest fecundity is highest in populations along the southern U.S. Atlantic coast and lowest among those in the northern range (Walburg and Nichols 1967). The percentage of shad that undertake repeat spawning runs shows an opposite trend and increases from south to north (Walburg and Nichols 1967; Leggett and Carscadden 1978). Shad native to rivers north of latitude 35° are believed to experience lower post-spawn mortality than those in rivers south of this latitude (Weiss-Glanz et al. 1986).

Spawning migration timing for American shad is heavily regulated by water temperature. American shad occur in coastal rivers across a 4 to 25°C water temperature range, with a peak around 18°C (McDonald 1884; Massmann and Pacheco1957; Leggett

and Whitney 1972). In the Neuse River, North Carolina, Beasley and Hightower (2000) observed American shad migrating upstream when temperatures at the mouth of the river were between 18.6 ºC and 19.0 ºC.

Variability exists between studies as to specific habitat requirements for American shad spawning sites (Stier and Crance 1985, Ross et al. 1993). Depth at spawning locations is highly variable, with a reported range between 0.45 m and 10.0 m (Mansueti and Kolb 1953; Walburg 1957; Marcy 1972; Bilkovic 2000). American shad spawning in the Neuse River predominantly occurred in depths less than 2 m (Beasley and Hightower 2000). Eggs have been collected at velocities ranging from 0.15 to 0.61 m/s (Marcy 1972; Williams and Bruger 1972). Ross et al. (1993) found no correlation between spawning activity and water velocity. However, Walburg (1960) concluded that sufficient current is required to buoy eggs in the water column to maximize hatching success. Bowman and Hightower (2001) and Hightower and Sparks (2003) found substrates dominated by cobble at American shad spawning sites. However, Massmann (1952) reported high concentrations of eggs over sandy bottoms free of mud and silt. Bilkovic (2000) asserted that sediment size was not an important factor in determining habitat suitability.

Spawning typically occurs from sunset to approximately midnight (Massman 1952; Chittenden 1969) and often involves a single female and group of males. Spawning is often characterized by splashing or "fighting" at the surface (Leim 1925). Eggs are considered demersal and quickly become non-adhesive after release and begin to sink once water-hardened (Chittenden 1969; Rulifson 1994). Drifting eggs have been found to

lodge in downstream substrate or travel several kilometers from the spawning grounds (Chittenden 1969; Marcy 1972). Massmann (1952) suggested high current velocity and water turbulence increase distance traveled by newly spawned eggs.

American shad eggs undergo rapid development during the first 48 hours after fertilization (Jones et al. 1978 and references therein). Eggs typically hatch in two days post-spawn at water temperatures of 12°C, but may take up to 17 days at temperatures of 27° C. Larvae drift downstream until they are free-swimming and begin to utilize fresh and brackish water nursery habitat. Young-of-the-year American shad move into estuarine habitats as they continue their seaward migration (Jones et al. 1978). Juvenile American shad generally remain in riverine or estuarine areas until the fall of their first year, then move offshore when temperatures fall below 15ºC (Walburg and Nichols 1967).

Striped bass

Male striped bass can mature as early as two years; however, both sexes typically reach maturity between ages three and six (Setzler et al. 1980; Olsen and Rulifson 1992). Lewis (1962) found virtually 100% maturity by age seven for fish collected from North Carolina, Connecticut, and California. Striped bass are found to be highly migratory in both saltwater and freshwater environments (Raney and Sylva 1953; Rulifson and Dadswell 1995). For example, fish spawned in the Hudson River and tributaries of the Chesapeake Bay will move northward along the coast in the spring, spend summer in coastal waters of mid-Atlantic and New England states, and return south along the coast in

fall (Boreman and Lewis 1987; Dorazio et al. 1994). However, many southern populations are different in that a large percentage of adults reside in the lower-river or estuary throughout the winter as opposed to making coastal migrations (Raney 1952; Chapoton and Sykes 1961; Rulifson et al. 1982).

Striped bass experience a similarly wide range of water temperatures (4 to 27°C) as that of American shad during their spawning migration (Talbot 1966). Beasley and Hightower (2000) found striped bass on the spawning grounds of the Neuse River, North Carolina at temperatures between 13.9°C and 23.2°C. Spawning grounds for striped bass are typically in shoal areas where boulder substrate and higher current velocities are present (Raney 1952; Mansueti and Hollis 1963; Talbot 1966; Beasley and Hightower 2000). Bayless (1967) found higher egg survival when spawning occurred over large substrate or when flow conditions kept eggs suspended in the water column.

Striped bass spawning is generally greatest in late afternoon and early evening (Jones et al. 1978; Rulifson and Manooch 1990). Striped bass eggs are semi-buoyant and rely on sufficient streamflow to prevent sinking and allow ample time for development (Mansueti 1958). Egg development is dependent on water temperature and hatching typically occurs within 29 to 48 hours after release (Jones et al. 1978 and references therein; Setzler et al. 1980; Boreman 1983). Eggs progress through several stages of development as they remain suspended in the water column and once larvae become free-swimming juveniles they move into nearshore estuarine habitat to feed (Jones et al. 1978 and references therein; Boynton et al. 1981.) Most anadromous striped bass live in estuarine

waters for the first several years of life, then migrate to coastal waters to feed and overwinter (Richards and Rago 1999).

Study Area

The Cape Fear River Basin is the largest watershed in North Carolina, with a total drainage area of 23,310 km^2, and contains 27% of the State's population (Mallin et al. 2008). The Cape Fear River flows south/southeast, approximately 320 km from the confluence of the Deep and Haw rivers in Chatham County, North Carolina, to the Atlantic Ocean, 40 km downstream of Wilmington, North Carolina (Walburg and Nichols 1967). Because of the open connection with the Atlantic Ocean, tidal effects are detectable 97 rkm upstream at the first lock and dam (Mallin et al. 2008). Channel morphology and substrate types are distinct between the upper and lower portions of the river. Above the fall line, substrates are dominated by coarse rocky material and exposed shoals are common. In contrast, the lower river has relatively monotypic depth and substrates are dominated by sand and fine material.

Swamp forests comprise most of the land surrounding the lower tidal portion of the river (Mallin et al. 2008). Timber harvesting is an important industry in the watershed due to the large amount of forested land. Crop agriculture is the single largest use category and represents 22% of the land coverage. The remaining land coverage is comprised of forest (38.7%), water (15.8%), urban (10.1%), grassland (9.1%), shrubland (3.7%) and barren (0.3%) (USGS 2008). The Cape Fear is the most heavily industrialized basin in

North Carolina, with numerous industries utilizing the Cape Fear River in the upper watershed and 11 major industrial dischargers in the tidal basin itself (Mallin et al. 2008).

Methods

Egg Sampling

Egg surveys were conducted twice a week from March 9 through May 31, 2007 and March 5 through June 4, 2008 at five locations (Figure 1). One sampling location was established within 0.5 km downstream of each lock and dam (rkm 97, 149, and 186). All lock and dam sites were sampled after sunset, with the exception of two samples in 2007. A fourth site was established in the city of Fayetteville, approximately 3 km above the NC 24 Bridge (rkm 226). The fifth sampling station was located just east of the city of Lillington in 2007, below a shoal at the NCWRC Wildlife Road access area (rkm 273). However, low water levels resulted in poor sampling conditions at this site, so in 2008, the location was moved 3 km upstream (rkm 276) to a site just upstream of the NC 401 bridge. Latitude and longitude for each site were determined using a Garmin Etrex Vista handheld GPS unit and surrounding physical landmarks were noted for reference.

Depth at each site was measured using an Eagle model Cuda fishfinder. Temperature and dissolved oxygen readings were taken using a YSI (Yellow Springs Instrument) handheld multi-parameter water quality unit (moled 85). Plankton samples were collected using a bongo style net consisting of two 0.3-m hoops with 500-µm mesh, 6:1 tail-to-mouth ratio nets, and solid cup cod ends. A weight was attached to the crossbar

of the frame in order to reach bottom. A General Oceanics Model 2030R flowmeter was used to calculate the volume of water sampled during each collection effort. A 2.27-kg weight was attached to the lower line of this unit to reach bottom. Once in position, both rigs were slowly lowered off the stern of the vessel until the weights made contact with the bottom. This would begin the 15-minute oblique tow, in which the instruments were raised at consistent intervals to sample the entire water column evenly. The rope attached to each instrument was marked in 0.3-m increments to ensure consistency between retrievals. After 15 minutes, the net and the flowmeter were removed from the water.

The walls of the net were washed down into the solid cup ends and the contents of the cups were then fixed with a 5-10% solution of formalin and labeled for processing. Processed American shad eggs were categorized by developmental stage using criteria provided by Jones et al. (1978). Stages were as follows: (1) first two hours of development; (2) 4 to 6 hours; (3) around 20 hours; (4) around 38 hours; (5) 42 hours and beyond. American shad larvae were collected during the study, but numbers were insufficient for useful analyses. Relatively small numbers of non-target species eggs and larvae were also collected, but were likewise not used in analysis.

In 2008, observations of American shad spawning activity were also noted during egg sampling events. Presence of spawning activity was determined through auditory or visual detection of the characteristic behavior of spawning American shad. The behavior, often referred to as “fighting”, is characterized by one or more male American shad moving along side a female American shad in a circular motion at the surface of the water

(Leim 1924; Ross et al. 1994; Bowman and Hightower 2001). Fish typically turn on their sides and vibrate against one another during this motion, which creates an audible and visual disturbance in the water.

Egg Data Analysis

Only American shad egg data were included in the statistical analysis due to the extremely low numbers of striped bass eggs collected during the course of the study. Stage-1 American shad egg densities (eggs/m^3) were calculated for each sampling station by dividing the number collected by the volume of water sampled. A nonlinear regression equation was used to examine the relationship between the density of stage-1 American shad eggs and sampling location. Least-squares parameter estimates were obtained using the Solver function in Microsoft Excel.

Logistic regression using presence/absence of American shad eggs was used to investigate factors affecting spawning activity. Due to the absence of eggs in samples from sites upstream of the locks and dams, only data from the sample sites below each lock and dam were included in the analyses. Sample times were assigned to hour (e.g. 20:00-20:59 = 20:00) to examine temporal differences in egg collections. Factors evaluated using logistic regression were water temperature (C), dissolved oxygen (mg/L), and streamflow (m^3/s).

Multiple regression analysis was used to examine the effects of sample location, sample time, and water temperature on American shad egg densities. Due to the

frequency of zero values and hence non-normally distributed data, a count of 0.5 was added to the total number of eggs collected during each sample event. Egg density values were then recalculated and $\log_e$ transformed for analysis. Statistical significance for all analyses was based on an alpha value of 0.05.

Tag Retention

The tracking objective of this project consisted of several phases, one of which was to determine how American shad would react to the proposed tagging procedure. A tag retention study was conducted in 2007 at the NCWRC's Watha Hatchery in Pender County. NCWRC biologists collected 25 American shad on April 2, 2007 by boat electrofishing below LD-1. The fish were transported to the facility in a 378 liter, round live-well and placed into a large round indoor hatchery tank for recovery. On April 4, 2007 we implanted VEMCO V9-1L-R04K coded transmitters in ten of the fish, with the remaining fish serving as controls. Tagged fish were netted from the tank, quickly measured, assigned sex if possible, implanted with a transmitter, and returned to the tank. Transmitters were 24 mm long, weighed 2.2 g in water, and were inserted into the gut through the esophagus using a small length of clear tubing with glycerin lubricant. The fish were held for a five-day observational period over which mortality and tag retention were recorded.

Fish Collection and Tagging

Protocol for telemetry work conducted in 2008 differed from that used in 2007. In 2007, American shad were collected 24 April – 14 May and striped bass collections occurred 13 April – 7 May. In 2007, American shad and striped bass were collected from areas below the locks and dams, and then transported upstream of the locks and dams to rkm 219 to be tagged and released. Fish were collected by NCWRC biologists by electrofishing and were held in a round 378-liter onboard livewell, which included a circulating system, and an airstone that was fed directly from a tank of 100% oxygen. The first six striped bass collected were taken directly to the Pechmann Fishing Eduction Center in Fayetteville to be held until they could be processed. All other fish were transported directly from the collection location to the release point, just downstream of the NC 24 Bridge (rkm 219). On several occasions, fish were moved from the NCWRC livewell into a 378-liter plastic oval tank onboard a boat. This tank was equipped with a circulation system, sprayer hose, and oxygen-fed airstone, and held the fish during transport to the release site.

At the release site, live fish were measured (total length, TL, in mm), examined to determine sex, tagged, and placed into an instream holding pen. The American shad were implanted using the same type of VEMCO transmitter and method as discussed in the tag retention section. Striped bass received a similar but larger (36 mm, 6 g in water) V13-1L-R64k coded transmitter through surgical implantation, following the methods used by

Haeseker et al. (1996). Striped bass were placed into a tub of water prepared with Tricaine Methanesulfonate [Finquel® (MS-222)] anesthetic to induce sedation. Each fish was then placed ventral side up, into a foam-lined trough that stabilized the fish during surgery. The trough was positioned atop a cooler of water prepared with a weak solution of MS-222. Sedation and oxygen flow during surgery were maintained by re-circulating the solution from the cooler into the oral cavity and across the gills. A small incision was made along the centerline of the ventral body cavity wall posterior to the pelvic fins but anterior to the vent, into which the transmitter was inserted. Gonads were also visible through the incision and therefore sex could be verified. The incision was then sutured and antiseptic ointment was applied to the wound. Fish were placed in a recovery tank or held by hand in the river current until able to swim away under their own power.

To hold telemetered fish in 2007, I constructed a 1.5 m wide x 3.4 m long x 1.3 m deep floating oval frame made of polyvinyl chloride (PVC) pipe, with custom 0.63-cm ace knotless netting (Midlakes Corp., Knoxville, TN). The number of fish tagged on each occasion varied depending on the number captured, so different combinations of tagged and untagged fish were held in the pen to see if it affected the response of the tagged fish upon release. Also, some fish were held in the pen for 24 hours prior to release while some were released directly into the river. Holding times, pen arrangements (door open vs. door closed), number of fish in the pen, and release (immediate vs. delayed) were purposely varied among release events in order to see how these different approaches affected tagged fish behavior after release.

The poor performance of telemetered fish in 2007 led us to abandon the trap and transport method in 2008. All fish in 2008 were tagged and released at their capture sites. In 2008, American shad were collected 13 March – 25 March and striped bass collections took place 26 February – 21 April. Two striped bass were caught and released downstream of lock and dam 2 (LD-2) ; all others were captured, tagged, and released from locations downstream of LD-1 . All but one striped bass and eight of 20 American shad were collected by NCWRC biologists by electrofishing. The remaining fish (12 of 20 American shad, one striped bass) were captured using hook and line. The single striped bass was caught approximately 200 m downstream of LD-1 using a piece of fresh-cut American shad. The first two American shad were caught within 75 m of the dam at LD-1 using shad darts on light-tackle spinning rods. Robin Hall (lockmaster at LD-1) advised angling for American shad inside the lock chamber at LD-1. He had observed American shad congregated near the upstream gate of the lock chamber, where attractant flow generated by an open valve in the gate created a boil of water against the lock wall. With his assistance, I captured the remaining 10 American shad in one short effort. The boat was tied off inside the lock chamber and fish were processed on board. The same tag types and implantation procedures used for both species in 2007 were used again in 2008.

Tracking

Monitoring fish movement after release was the final phase of the telemetry work. All transmitters emitted a unique sequence at random time intervals that allowed for

individual identification. Time intervals between coded tag bursts were set at once every 30-60 seconds for American shad and 60-90 seconds for striped bass. I incorporated two different methods of transmitter detection. One method included an array of six stationary VEMCO VR2W receivers in 2007 and 10 receivers in 2008 (Figure 2). In 2007 one receiver was deployed at I-295 bridge (rkm 231), NC 301 bridge (rkm 220), I-95 bridge (rkm 212), and Lock and Dam 3 (LD-3) (rkm 186) on April 12 and at LD-2 (rkm 149) and LD-1 (rkm 97). All receivers, except the one at the 301 bridge which was missing, were removed from the river on June 12. In 2008, four additional receivers were added to the 2007 array. One of the four was the missing receiver from the end of the 2007 season which had washed downstream but was recovered in 2008. The four new locations were inside the lock chamber at LD-1, at rkm 246, the NC 217 bridge in Erwin, NC (rkm 261), and at the NC 401 bridge in Lillington, NC (rkm 276).

Each stationary receiver was attached to a length of braided nylon rope with a weight attached to the bottom and a large foam float tied to the top. This arrangement allowed the receiver to be suspended in the water column in order to maximize reception capability. A second length of rope was tied to a permanently fixed object in the river and then attached to the weight to prevent the receiver from being swept downstream during high flow events. These receivers operated continuously and automatically logged any detection event. The unique tag identification number, date, and time were recorded for each signal detected by the receiver.

Manual tracking was conducted by boat, using a portable VEMCO VR100 receiver equipped with either a VH165 omni-directional or VH110 directional hydrophone. Relocation coordinates were logged using the receiver's internal GPS unit. Date, time, depth, temperature, dissolved oxygen, and flow rate measurements were also taken, along with a Petite Ponar sample to determine substrate. Streamflow and precipitation data were obtained from the USGS at http://waterdata.usgs.gov/nwis/sw for USGS site number 02105769 at LD-1.

Detection Probability

Estimates of detection probability were determined for most stationary receivers using detection histories from 2007 and 2008. Separate probabilities were calculated for American shad and striped bass in both years. Probabilities were calculated for a given receiver (B), with a downstream receiver (A) and an upstream receiver (or manual relocation point) (C) on either side. Detection probability for receiver B was estimated by dividing the number of fish that passed from receiver A to C and were detected by receiver B by the total number of fish that passed from receiver A to C. Separate estimates were made for upstream and downstream movements. Logistic regression analysis was performed to examine the effect of receiver station location and travel direction on receiver detection for both species.

Receiver Detections and Relocations

Results from stationary receivers and manual tracking events were used to characterize the migration of telemetered American shad and striped bass. Minimum extent of upstream migration was established for each fish based on the furthest upstream stationary receiver detection or manual relocation. Upstream passage efficiency through the locks and dams was calculated for both species in 2008. Calculations were based on the number of fish that could potentially be present downstream of a lock and dam divided by the number of those fish detected by the receiver upstream of that lock and dam. For striped bass, the potential number of fish present downstream of LD-1 was established by confirmed detections on the receiver located inside the lock chamber of LD-1. This estimate may slightly overestimate passage due to fish that may have returned to the dam but were not detected by the chamber receiver. Due to the fact that American shad were tagged and released prior to the deployment of the chamber receiver at LD-1, the potential number present downstream of LD-1 was the total number of American shad tagged and released during 2008. Therefore, the passage estimate obtained using this number may be more conservative than that of striped bass. This also does not account for any handling stress bias that may have influenced American shad migratory behavior.

Migration Rate Analysis

Upstream migration rates (km/hr) of 2007 and 2008 sonic-tagged American shad and striped bass were determined using a calculation similar to one used by Katz (1986)

for American shad in the Connecticut River. Calculated migration ratess are relative to water velocity and take into account the additive effect of water current speeds that fish must overcome to achieve upstream movement. For example, a fish traveling upstream at 1 km/hr, in a current velocity of 1 km/hr has a migration rate of 2 km/hr. The equation for upstream migrants was $S = (D / T) + V$, where D = distance in kilometers between two stationary receivers, T = time in hours between the last detection a particular downstream receiver (start rkm) and the first detection at the next upstream receiver (end rkm), and V = water velocity in kilometers per hour. Ground speeds ($S = D/T$) are also given for comparison with studies where water velocity was not taken into consideration for migration rate calculations.

Water velocities (V) used for the migration rate calculations were determined using the linear regression equation ($y = 0.007x + 0.9772$, $R^2 = 0.691$), which assumes a linear relationship between the independent (x) variable instream flow (m^3/s) and the dependent (y) variable water velocity (m/s) (Figure 3). The regression equation was obtained using observed velocity values taken during egg sampling events and USGS average instream flow values on those dates. The instream flow value used to calculate migration rate for a particular fish's migration from one receiver to the next was the median from all the USGS instream flow values observed between the starting and ending dates. USGS instream flow data were available from three locations along the Cape Fear River (rkm 97, 186, and 276). Flow values were chosen based on the location of the receivers used to calculate a fish's distance traveled. Migration rates were also reported in

terms of fish body length per second (BL/s), which entailed converting the original relative speed calculations from km/hr to cm/s and dividing that figure by fish total length in cm.

One-way analysis of variance (ANOVA) and multiple regression were used to examine relationships between migration rates and biological and spatial parameters. Primary factors of interest were start rkm of the migration calculation and fish length.

Results

Egg Sampling

Average water temperature, dissolved oxygen level, and sample volume were fairly similar among plankton sampling sites and between sampling seasons (Table 1). Average sample depth was greater at sites below the locks and dams in both seasons. Mean water temperature was about 1° in 2008 (Table 1). Streamflow at LD-1 ranged from 23 m^3/s to 510 m^3/s, with an average of 163 m^3/s in 2007 and from 26 m^3/s to 700 m^3/s, with an average of 134 m^3/s in 2008 (Figure 4). Nineteen rain events, totaling 23.42 cm of rainfall, occurred during the 2007 season, with five events resulting in accumulation greater than 1.27 cm. Thirty-four rainfall events, totaling 26.47 cm, occurred during the 2008 season, with four events resulting in accumulation greater than 1.27 cm (Figure 4). Average daily precipitation in 2007 was 0.25 cm, with a maximum accumulation of 9.70

cm on April 15, and 0.28 cm in 2008, with a maximum accumulation of 6.63 cm on April 5.

Egg Data-American Shad

A total of 586 American shad eggs were collected in 2007 and 728 in 2008 from the five sampling locations (Table 2). Egg collection results for all samples are given in Appendix A. The earliest American shad egg collected during the study came from below LD- 2 on March 17, 2008, at a water temperature of 14.0°C. This collection came just after the USACOE began their multiple daily locking procedures at each lock and dam. The earliest date of collection at LD-1 was March 28, compared to April 12 for LD-3 and April 22 for Fayetteville. The last date of collection at any site was May 30, 2008 at water temperature 25.4°C. For both years combined, site LD-1 yielded 1083 eggs or approximately 82% of the total number collected during the study, compared to 154 eggs (12%) at LD-2, 72 (6%) from below LD-3, and 6 (0.003%) from the site near Fayetteville. No eggs were collected from the Lillington site in either year. Stage 1 eggs (age 0-2 hrs) made up 95% of total American shad eggs collected, with 4% found to be in stage 2 (Table 2).

Average density of American shad eggs was 122.4 (SD ± 229.1) eggs/1,000 m^3 among sites in 2007 and 100.4 (± 185.3) eggs/1,000 m^3 in 2008, with highest densities collected at the LD-1 site in both years. Peak densities of stage-1 American shad eggs collected from a single sample, 6161 eggs/1,000 m^3 in 2007 and 4984 eggs/1,000 m^3 in

2008, occurred below LD-1. In 2007 and in 2008, density declined at an exponential rate moving upstream from the lowermost site at LD-1(Figures 5-6). Fitted curves from least squares regression analysis indicate that egg density decreases by about 90% with each additional lock and dam.

Water temperature was found to be highly correlated (p=0.0337) to presence/absence of American shad eggs in samples. I did not detect a significant relationship between streamflow (p=0.1730) or dissolved oxygen (p=0.5533) and presence/absence of American shad eggs in samples, despite the fact that spawning activity often appeared to increase as flow decreased following a spike in streamflow (Figure 7-14). The linear and quadratic terms for temperature were significant, so the final model for probability of egg absence (SAS Institute Inc. 2007) was

$$y = \frac{1}{1 + e^{-(\beta_0 + \beta_1(temp°C) + \beta_2(temp°C)^2}}$$

(Table 3, Figure 15). The model illustrated the non-linear relationship of water temperature to the presence/absence of American shad eggs within samples. The probability that at least one egg would be present peaked near 20°C, with probability declining to approximately zero at water temperatures around 12 and 29°C.

Least squares regression modeling shows a significant effect of sample location *(p = 0.0065)*, sample time *(p = 0.0021)*, and water temperature *(p = <0.0001)* on the density (eggs/m^3) of American shad eggs collected by plankton sampling (Table 4). The estimated

least square mean was highest below LD-1 and decreased for each upstream lock and dam (Figure 16), although the decline was less dramatic than predicted from the simple exponential model relating egg density to sampling location. Likewise, estimates indicate samples taken between 20:00 and 21:00h produced highest densities of American shad eggs. The model includes a significant linear effect of water temperature on egg density. A quadratic term for water temperature was not significant for density, unlike the logistic regression model for egg presence/absence.

Egg Data-Striped Bass

No striped bass eggs were collected during the 2007 season; however, similar efforts yielded 41 eggs in 2008 (Table 5). The earliest collection of striped bass eggs occurred on April 30 at LD-3, and one day later at both LD-2 and LD-1. The last collection of striped bass eggs from any site occurred on May 15, 2008 at LD-1. In 2008, all sites except the uppermost site in Lillington produced at least one egg. The majority (29 eggs, 71%) of striped bass eggs were collected at LD-3. Only seven eggs (17%) were collected at LD-1, four (10%) at LD-2, and one (2%) from the Fayetteville site. Average density of eggs collected in 2008 was 45.9 (± 97.3) eggs/1000 m^3, with highest densities collected at LD-3. Sample sizes were small but a majority of striped bass eggs (56%) were in the first stage of development, with all but two of the remaining eggs (39%) in the third stage.

Spawning Observations

In 2008, American shad spawning activity was only observed at sampling sites below the three locks and dams. Seventeen (65%) of the 26 observations of spawning were made at LD-1, with 7 observations at LD-2 and 2 observations at LD-3. Spawning activity was documented at LD-1 between 17 April 2008 and 4 June 2008, over a 17.1°C to 26.1°C range of temperatures and 20:37 to 00:00 time range. Observations made at LD-2 came between 21 April 2008 and 27 May 2008, over an 18.3°C to 23.4°C range of temperatures and 20:40 to 23:09 time range. Only two observations were noted at LD-3 on 6 and 13 May 2008 at 20:35 and 21:45 respectively, with water temperatures around 21°C.

Tag Retention

The tag retention experiment in 2007 resulted in an 80% post-tagging survival rate for tagged fish (Table 6). Three of the original 25 fish died in transit before the tagging procedure and one fish died due to improper tag insertion (ruptured viscera), leaving 21 fish for the experiment. Only two of the 10 tagged fish died (one within 12 hours of tag insertion and the other three days after tag insertion) and none of the 11 untagged fish died.

Migratory Characteristics

Twenty American shad and 20 striped bass were tagged and tracked during each year of the study. The group of American shad consisted of eight males (mean TL 440 mm) and 12 females (mean TL 503 mm) in 2007 and 19 males (mean TL 427 mm) and one female at 505 mm TL in 2008 (Tables 7, 9). The striped bass group consisted of 16 males (mean TL 626 mm) and four females (mean TL 749 mm) in 2007 and 16 males (mean TL 630 mm) and four females (mean TL 756 mm) in 2008 (Tables 8, 10).

In 2007, 18 American shad were relocated at some point in the study, based on combined data from manual tracking and stationary receivers (Appendix B Figures 1-4). Twelve (60%) American shad moved upstream of the release site and 6 (30%) moved downstream. Three of the six fish moving downstream went below LD-3, and none of those made secondary upstream movements. American shad 2428 was detected at LD-3 and made a secondary upstream movement, but it is unclear as to whether or not the fish moved downstream over the dam and then back upstream. Three American shad moved upstream of the uppermost receiver at rkm 231 based on manual relocations. One other American shad was detected by this receiver, but there is insufficient evidence to suggest that it moved upstream beyond that point. Unfortunately, manual tracking above rkm 231 was limited to three events (May 16, May 24, and June 7) due to logistics, time, and access restraints. The uppermost relocation was at rkm 252, based on manual tracking (Appendix B Figure 3).

Nineteen striped bass were relocated in 2007 and all fish immediately moved downstream of the release site at rkm 219 (Appendix B Figures 5-8). Two striped bass that initially moved downstream, within range of the receiver at LD-1, made secondary movements upstream using the fish locking procedure (Appendix B Figure 6). Striped bass 3276 (586-mm male) successfully locked through LD-2, while striped bass 3275 (589-mm male) passed back upstream of LD-2 and LD-3, and continued on past the furthest upstream receiver located at rkm 231. Although these fish were not manually detected below LD-1, I speculate that both fish fell below LD-1 and later locked through LD-1 as they began their secondary upstream movement. This is based on the large gap in time between detections at LD-1 in between downstream to upstream movements.

In 2008, 15 American shad and 16 striped bass, including two striped bass tagged in 2007, were relocated by stationary receivers or by manual tracking efforts. Thirteen American shad and 12 striped bass made movements upstream through at least one lock and dam (Figure 17). Seven American shad and four striped bass migrated upstream above LD-3 and all but two of these fish moved upstream to or beyond rkm 231 where shoal habitat first becomes present in the river.

The maximum documented upstream migration was made by striped bass 3274, a 761-mm male from the 2007 group of tagged fish. The fish was found by manual tracking on May, 7 2008 at rkm 299 just downstream of Buckhorn Dam (rkm 300), which represents the end point for upstream migration. The maximum distance for American shad was also recorded by manual tracking. American shad 10246, a 442-mm male, was

released on March, 25 2008 and detected at rkm 280 on May 7, 2008. Migration of each fish released in 2008, as detected by stationary receivers and manual tracking, is illustrated in Appendix C.

Passage Efficiency

Passage rates for American shad were 65% (13 of 20) through LD-1, 85% (11 of 13) through LD-2 and 64% (7 of 11) through LD-3. Striped bass passage results were relatively similar, with 77% (10 of 13) through LD-1, 75 % (9 of 12) through LD-2, and 44% (4 of 9) through LD-3. Note that the number in striped bass available for passage at LD-2 (12 fish rather than the 10 passing LD-1) was due to the collection and release of two striped bass in 2008 downstream of LD-2. These fish were not counted in the available pool of fish starting migration downstream of LD-1 but were subsequently added in to those with potential to move upstream of LD-2.

Detection Probability

American shad detection probabilities were calculated for eight stationary receivers for fish moving upstream and four stationary receivers for fish moving downstream (Figure 18). Probabilities of detection were similar for upstream (60-100%) and downstream (67-100%) moving fish. Upstream detection probability appeared lower in the uppermost section of the river (rkms 246 and 261). Downstream detection probability was 100% for all but one receiver (rkm 186, 2 of 3 fish detected) from which

data were available. Logistic regression analysis showed no significant effect of station location *(p* = 0.4406*)* or travel direction *(p* = 0.6802*)* on detection probability of American shad, although the analysis was based on very small sample sizes for all receivers.

Striped bass detection probabilities were calculated for eight stationary receivers for fish moving both upstream and downstream (Figure 19). Probabilities of detection were similar for upstream (50-100%) and downstream (67-100%) moving fish. Upstream detection probability was lower in the upper river section (rkms 231 and 246). Similar to American shad results, downstream detection probability was 100% for all but one receiver (rkm 231, 3 of 4 fish detected) from which data were available. In this case, logistic regression analysis indicated a significant effect of station location *(p* = 0.0024*)* and marginally insignificant effect of travel direction *(p* = 0.0708*)*. As for American shad, this analysis was based on small sample sizes at all receivers. A more intensive study, using a greater number of tagged fish, would be needed to thoroughly evaluate detection probability.

Migration Rate Analysis

Upstream ground speeds averaged 1.1 km/hr (range 0.08-4.3 km/hr) for American shad and 1.3 km/hr (range 0.08-3.7 km/hr) for striped bass. Migration rates adjusted for flow averaged 3.2 km/hr (range 1.4 - 6.4 km/hr) for American shad and 3.0 km/hr (range 1.3 - 5.5 km/hr) for striped bass. Migration rates, in terms of speed by body length (BL),

were also calculated using an adjustment for flow. American shad swam at a mean rate of 2.00 BL/s (range 0.7 - 4.1 BL/s), while striped bass averaged 1.3 BL/s (range 0.50 - 2.4 BL/s)

Migration rates appeared to be somewhat greater from rkm 186 (upstream of LD-3) to rkm 212 for both species (Figures 20-21). However, ANOVA results showed no significant effect of starting rkm *(p* = 0.1827*)* on migration rates of American shad. Regression analysis also revealed no significant relationship between start rkm or fish length and migration rate.

Similar ANOVA testing and regression analysis for striped bass indicated starting rkm has a significant effect ($p = 0.0118$ and $p = 0.0100$) on migration rates. Analyses indicated fish swam at higher speeds in the middle section of the river, upstream of LD-3 (Table 12). As with American shad, regression analysis revealed no significant correlation between fish length and migration rate.

Discussion

Egg Sampling

The plankton sampling strategy used during this study proved to be more effective for collecting American shad eggs than the approach used during a similar study on the Cape Fear River in 2006 (Dial Cordy and Associates 2006). In both cases, samples were taken downstream of the locks and dams, but my sampling was conducted during dusk

and evening hours, while those in the DCA study were taken during the day. The increased success rate is consistent with findings in the literature that the timing of spawning for American shad is concentrated around the early evening hours (Massman 1952; Walburg and Nichols 1967; Chittenden 1976; Ross et al. 1993). My analysis showed samples taken between 20:00 and 21:00h were most likely to have higher densities of American shad eggs. This finding is similar to that of Hightower and Sparks (1998) who found higher numbers of eggs in samples around 21:00h. In addition, Ross et al. (1993) found that American shad eggs were most numerous in samples taken between 20:00 and 24:00h on the Delaware River. The timing of sampling is particularly critical for a site below an obstruction, because spawning fish are likely to be immediately upstream of the sampling site.

Spawning Observations

Evening observations of American shad spawning made during the current study further support previous findings on timing of spawning. Spawning activity was most prevalent from mid-April to early-June, during the 20:00 to 24:00h time period, and at temperatures between 17 and 26°C. These ranges of dates, times, and water temperatures are similar to those of Bowman and Hightower (2001) for American shad in the Neuse River, as well as Ross et al. (1993) for American shad in the Delaware River. Spawning activity showed a similar pattern as that of egg density, with most observations occurring at the site downstream of LD-1. Spawning activity on the Cape Fear River was typically

observed near the shoreline on both sides of the river. More extensive observations of spawning activity would be required to determine whether this pattern is consistent at all spawning locations along the river.

Spawning Distribution

American shad eggs were collected at a range of water temperatures consistent with previous studies (Table 13) and very similar to the range of temperatures for observed American shad spawning activity in the Neuse River (18-23.7°C; Beasley and Hightower 2000). I found a significant relationship between water temperature and density of American shad eggs. Streamflow and dissolved oxygen were not significantly related to egg density, although this could be due to the fact that the observed values for both parameters were consistently in the range of suitability for American shad spawning (Stier and Crance 1985; Ross et. al. 1993).

Average densities of American shad eggs collected in my study (122.4 eggs/1,000m^3 in 2007, 100.4 eggs/1,000m^3 in 2008) were lower than those reported in other studies. Bilkovic et al. (2002) found higher densities of American shad eggs in two tributaries to the York River. They sampled 8 - 15 sites using a combination of plankton tows and push net samples from 1997 to 1999 and found an average of 591 eggs/1,000 m^3 in the Mattaponi River and 337 eggs/1,000 m^3 in the Pamunkey River. Smith (2006, Appendices I-J) reported very high mean densities of American shad eggs in the Tar River (11,000/1,000 m^3 in 2004 and 2,400/1,000 m^3 in 2005). The high estimates may be due to

the variability in Tar River flows, resulting in spawning being concentrated in relatively small volumes on some sampling occasions (R. Rulifson, East Carolina University, personal communication).

The egg distribution pattern at upriver sites in the current study remained consistent between years, despite the relocation of the uppermost sampling site in Lillington. Over the entire study period, only six American shad eggs were collected upstream of the locks and dams, all from one location at rkm 226. This finding is similar to that of DCA in 2006 on the Cape Fear River where only one American shad egg was collected upstream of the locks and dams at rkm 273 (Dial Cordy and Associates 2006). Coupled with the decline in egg collections from LD-1 to LD-3, this suggests that access to habitat above the locks and dams remains substantially limited.

The lack of eggs collected at upstream sites could be due in part to the inherent differences between upriver sites and those downstream of the locks and dams. Lock and dam sites tend to concentrate fish in one location, so samples taken below these obstructions are more likely to contain newly spawned eggs if spawning occurs. Evidence for this is seen in the fact that the vast majority (95%) of American shad eggs collected downstream of the locks and dams were in the first stage of development. Samples at upriver sites were not taken downstream of any barriers that may have concentrated fish and were therefore likely to capture eggs drifting from random upstream spawning locations. Such was the case on the Neuse River where American shad eggs were collected at multiple sites after the removal of a low-head dam (Burdick and Hightower

2006). Many of those sites were not immediately downstream of obstructions or known aggregates of fish and collections contained eggs at various stages of development. Similarly, Marcy (1972) collected American shad eggs up to 6.4 km from where the fish were assumed to spawn.

It is also possible (depending on streamflow and channel morphology) that American shad eggs, drifting downstream from upriver spawning events, may have settled out before reaching the upper basin sampling locations. Massmann (1952) suggested the distance traveled by newly spawned American shad eggs is positively correlated to water current and turbulence. The run-riffle-pool complex present in the upper portion of the Cape Fear River produces a much different flow regime than that of the lower river. During normal flow conditions, the upriver section contains more breaks in current velocity where drifting eggs may have an opportunity to settle out. Such variation could have limited downstream drift distance of eggs that were spawned upstream of my sampling locations. The upper basin sites also have more diverse substrates including gravel and cobble. This could have substantially limited downstream transport of eggs; for example, Chittenden (1969) observed stripped American shad eggs lodging in large substrates 1.5 to 1.8 m downstream of their release point.

Conducting day as opposed to night samples at upriver sites should not have negatively affected egg collections since I was not sampling downstream of known aggregates of fish. Many previous studies have resulted in successful collection of American shad eggs in daytime plankton samples (Massman 1952; Marcy 1972; Hawkins

1980; Burdick and Hightower 2006). However, if night spawning did occur in close proximity upstream of these sites, it is possible that drifting eggs may have passed by the site before samples were taken.

No striped bass eggs were collected in 2007 but successful collections did occur in 2008. However the number collected is still relatively low when compared to most other Atlantic drainages. For example, I collected an average of 0.32 eggs per 15-minute sample whereas Rulifson in 1991 collected an average of 14.9 striped bass eggs per 5-minute sample from two Roanoke River sites using a similar protocol (Rulifson 1992). My average density (46 eggs/1,000 m^3) was similar to estimates for the Neuse River (35-61/1,000 m^3, data from Burdick and Hightower 2006) but considerably less than for the Tar (1,440-1,520/1,000 m^3; Smith (2006) Mattaponi (2,053/1,000 m^3; Bilkovic et al. 2002), and Pamunkey 40,165 eggs/1,000m^3; Bilkovic et al. 2002). The estimated density of striped bass eggs in the lower Savannah River based on push-net sampling (2.65 eggs/1,000m^3; Wallin et al. 1994) was lower than my estimate for the Cape Fear.

The high numbers of striped bass eggs collected by researchers in other Atlantic drainages possibly reflect a positive response of striped bass to directed management efforts enacted to boost declining populations all along the Atlantic coast (Richards and Rago 1999; Bilkovic et al. 2002; Thomas 2002). However, based on current egg collection efforts, the Cape Fear River striped bass population appears not to have experienced such a positive response. Ashley and Rachels (2007) characterized the population of striped

bass in the Cape Fear as severely diminished and my findings still appear to reflect that assessment.

One point of interest about the 2008 striped bass egg collections is that the peak in the distribution of striped bass eggs appears to be below LD-3 unlike that of American shad, which is at LD-1. Furthermore, a large portion (39%) of those eggs were in the third stage of development, suggesting the presence of spawning upstream of LD-3. DCA saw similar results in 2006, with 9 of 37 striped bass eggs collected from a site downstream of LD-3 and 26 of 37 collected from a site approximately 22 rkm upstream of LD-3 (Dial Cordy and Associates 2006). These findings bring up questions about whether striped bass are selecting for spawning locations at or upstream of LD-3, or whether fish passage using the locks is more effective for striped bass than for American shad. Further egg collections are needed to determine if this trend is indicative of the distribution of striped bass in the Cape Fear River.

Sampling Efficiency

Differences in egg densities between this and other studies could be related in part to differences in sampling equipment. For example, some researchers have incorporated the use of bow-mounted pushnets to sample American shad and striped bass eggs (Wallin et al. 1994; Bilkovic et al. 2002). Their effectiveness relative to oblique tows would depend on the distribution of eggs within the water column. Some of the discrepancy between findings might also be related to overall population size. Systems containing

larger populations of spawning fish may inherently result in higher densities of eggs in samples. An example of this scenario would be the larger population of striped bass spawning in the Roanoke River system as compared to the Cape Fear River (Thomas 2002; Ashley and Rachels 2007).

Another potential factor is drainage size. A given run size (level of egg production) would result in a higher density in a smaller system, although the low streamflows often present in small systems could result in a quicker deposition of drifting eggs. For example, the Little River in North Carolina (tributary to the Neuse) has a decent run of American shad and river volumes are sometimes low due to variable flows, but eggs are rarely collected due to the low flows and braided stream reaches (Burdick and Hightower 2006;). Larger systems would result in a lower egg density for a given run size but might be more likely to keep eggs suspended.

The inherent high water velocities often associated with high streamflows may negatively affect sampling efforts. Such an effect was apparent during several of my sampling events where high flows prevented sampling or pushed the plankton net toward the surface, making it impossible to obtain a sample from the lower portion of the water column. This problem could result in an underestimate of eggs for both species.

Telemetry

American shad and striped bass demonstrated very different reactions to trap and transport activities in 2007. Many previous studies have shown that both American shad and striped bass exhibit a strong "fallback" response (movement downstream after release) to the handling stress of tagging procedures (Barry and Kynard 1986; Beasley and Hightower 2000; Moser et al.2000; Bowman and Hightower 2001; Hightower and Sparks 2003). I found this response to be less intense in American shad than in striped bass. Only 9 (45%) American shad moved downstream after release; however, three fish later moved back upstream for a total of 12 (60%) fish relocated at or upstream of the initial release point. These results are in the range of those of Moser et al. (2000) who saw 39% - 95% of telemetered American shad returning upstream to the lock and dam after an initial downstream movement.

Striped bass, on the other hand, responded very poorly to stress, with all fish making immediate downstream movements upon release. These findings are similar to those of Carmichael et al. (1998) who saw substantial downriver movement of telemetered striped bass in the Roanoke River. However, two striped bass made secondary movements upstream and both fish made use of the locking procedure at more than one lock and dam. This claim is based on the fact that water levels during the periods in which they moved beyond the dams were insufficient to provide passage over the dam.

The changes in telemetry protocol in 2008 were based on the poor previous results in 2007 and the findings of other investigators (Moser and Ross 1993; Carmichael et al.

1998; Bowman and Hightower 2001). The decision to abandon the trap and transport approach was aimed at minimizing the handling stress fish would undergo prior to release. Instead of trap and transport, fish in 2008 were captured, tagged and released at the same location. To further improve fish response to tagging, an effort was made to collect fish from areas at or downstream of LD-1, as early in the year as possible. Earlier collection times provided cooler water temperatures and allowed for increased recovery time before the spawning run. The cooler water temperatures earlier in the season may have allowed fish to better handle the stress of capture and tagging.

Such an approach was used by Carmichael et al. (1998) in the Roanoke River. They collected striped bass for the 1994 spawning season from the Albemarle and Croatan sounds between December 1993 and March 1994. Their results show 25 of 41 striped bass tagged with sonic transmitters and released prior to the spawning season entered the Roanoke River. My decision to change protocol appeared to be correct based on the number of fish that moved upstream after release and the number of fish that moved above all three locks and dams. Limiting handling stress should be a goal of similar projects in the future in order to improve post-release migration.

On a similar note, the use of hook and line to collect fish for tagging appeared to lead to greater post-release movement upriver. Although I was largely unsuccessful in obtaining striped bass using this method (one fish), it was particularly effective for capturing American shad. Eleven of the 12 American shad collected on hook and line made movements upstream of LD-1. Ten of the 12 hook and line captured American shad

were collected on the same day from inside the lock chamber at LD-1. These 10 fish were released inside the chamber after tagging and all made movements upstream of LD-1. Ely (2008) used hook and line to collect Alabama shad for a tagging study on the Apalachicola River. This method was also incorporated by the Maryland Department of Natural Resources as a low-cost and non-lethal way to collect broodfish for an American shad aquaculture program (Minkinnen and Richards 1998). I recommend using this method to collect all American shad in future studies to minimize handling stress and maximize potential for upstream movement after release.

Detection Probability

Overall, detection probabilities were acceptably high at all receiver locations. Differences in detection probability among receivers may be due to their positioning. Receivers just upstream of the locks and dams were placed within 250 m of the upper gate, on the same side of the river. Fish exiting the lock upstream would most likely be immediately detected due to this positioning. Receivers in the upper portions of the river may have been adversely affected by fluctuations in streamflow due to their position in areas with higher variation in channel depth. This effect would be a factor if low flows resulted in obstructions to detection (e.g. channel braiding, exposed boulders), or if high flows pushed receivers into a horizontal position near or onto the bottom of the river. Furthermore, increased channel width at one of my upstream sites (rkm 261) may have adversely affected detection probability.

Migration

Prior to 1900, the extent of migration for American shad in Atlantic coastal systems with substantial runs was 300 – 500 rkm (Stevenson 1899). However, the construction of small low-head mill dams, locks and dams, and large hydroelectric dams over the past century substantially limited the range of migration for fish in many of these rivers (Walburg and Nichols 1967). The locks and dams present in the Cape Fear River were constructed between 1913 and 1934; however they were not the first obstructions to impede the spawning runs of the river's anadromous fishes.

By 1852, 11 locks and dams had been constructed between Fayetteville, North Carolina (rkm 220) and the modern day site of Buckhorn Dam (rkm 300) to aid the passage of company ships bound for the coal fields of the Deep River Coal Company (Thompson 1852). This stretch of river includes the Smiley Falls area, which is considered to be the historical spawning grounds for American shad in the Cape Fear River (Nichols and Louder 1970). It also coincides with the natural shift in habitat that occurs in the river around rkm 231. This shift is associated with the geologic and topographic transition zone in North Carolina referred to as the "fall line" (Hack 1982). Much attention is given to the impact of the current locks and dams on anadromous fishes; however it is likely that migration has been affected by dams for a substantially longer period.

The upriver extension of the stationary receiver array in 2008 beyond rkm 231 allowed me to refine my manual searches in the upper river reaches, and thus more

effectively document the extent of migration of both species. The farthest upriver migration by an American shad during the study, based on manual relocation, was 280 rkm. Similar telemetry work by CZR in 2003 on the Cape Fear River showed a maximum American shad upstream migration of approximately 257 rkm (CZR 2004). I documented a maximum upriver migration of 299 rkm for striped bass. This fish was manually relocated less than one kilometer downstream of Buckhorn Dam, which represents the maximum possible extent of upriver migration. CZR (2004) also manually relocated a telemetered striped bass from their study just downstream of this barrier. Results from both studies demonstrate successful migration upstream of LD-3 by some American shad and striped bass.

These distances are similar to those traveled by anadromous species in other systems to reach spawning grounds or before reaching man-made obstructions. In the Roanoke River, the striped bass spawning grounds are 12 rkm downstream of a large hydroelectric dam (Carmichael 1998). In the Neuse River, Beasley and Hightower (2000) observed a maximum upstream migration of 224 rkm for American shad and 352 rkm for striped bass prior to the removal of a low-head dam at rkm 225. Bowman and Hightower documented migration extents of 241 rkm for American shad and 302 rkm for striped bass in the two years after dam removal. American shad in the Savannah River travel 295 -300 rkm to spawn downstream of a lock and dam (Bailey et al. 2004). In comparison, Chittenden (1976) observed American shad migrations of 430 rkm in the unobstructed Delaware River.

Six American shad and three striped bass were detected at or upstream of the receiver at rkm 231. This is the location where the habitat structure of the river begins to shift from a monotypic depth, flow, and channel shape to a more complex structure of shoals and pools. Five of the manually relocated American shad were found in shoal areas. Although these were just point locations and do not provide enough information to show patterns of selectivity, it does indicate that American shad move into areas with distinctly different habitat characteristics than that of the lower river. Detections from stationary receivers illustrate this movement in both species. Researchers in other coastal rivers of North Carolina have observed anadromous fish migrating to upriver spawning grounds where habitat structure is distinctly different than that of the lower river (Beasley and Hightower 2000; Hightower and Sparks 2003). Further concentrated efforts are needed to reveal any patterns in habitat selection in the Cape Fear River.

Migration Rate

Although the ranges of ground speeds for the two species were slightly higher than those seen in other telemetry studies, the means were similar. Katz (1986) calculated apparent (not adjusted for flow) speeds for American shad in the Connecticut River and found a mean of 1.6 km/h (range 0.4-2.4 km/h). Similarly, Hightower and Sparks (2003) calculated mean migration rate of migrating American shad in the Roanoke River at 0.99 km/h. Beasley and Hightower (2000) estimated migration rates ranging from 0.29 km/h to 1.5 km/h in 1996 and 0.23 km/h to 2.3 km/h in 1997 for sonic-tagged striped bass in the

Neuse River. Similarly, Kynard (1987) found striped bass migrating up the Connecticut River at a mean rate of 0.7 km/h (range 0.3 – 1.2 km/h); while Wingate and Secor (2007) saw Hudson River striped bass moving at a mean rate of 0.6 km/h (range 0.06 – 2.6 km/h).

Estimated migration rates in this study were obviously higher than the ground speeds because they adjusted for the velocity of the water. These adjustments were based on oblique measurements of current velocities at plankton sampling sites. They may overestimate migration rates if upstream-migrating fish are close to the shore or bottom where velocities would be lower. I could not find studies that reported ranges of migration rates for either species that were calculated using this adjustment. Speeds relative to flow seem more logical and appropriate for fish movement and therefore I chose to report them as such.

The significant difference of American shad and striped bass migration rates between receiver locations is possibly a function of the physical differences of the Cape Fear River itself. The slower speeds through the lower portion of the river are most likely linked to the presence of the locks and dams. Migrating fish would almost certainly experience a delay unless arrival at a particular lock and dam coincided with times when locking procedures for fish passage were occurring. Slower speeds found in the upper portions of the river may be due to the presence of shoal habitat. These areas may concentrate fish in a similar fashion as the locks and dams. Some fish may continue to move through these sections, while others may delay migration and use these areas for spawning. The faster migration rates in the middle portion of the river (rkm 187-230)

could be due to the absence of obstructions and hypothesized lack of suitable spawning habitat. Fish may be more likely to move through these areas of monotypic depth, substrate, and channel morphology, in route to upriver habitat where fish may be concentrated.

Leonard et al. (1999) conducted respirometer experiments and found that American shad migration efficiency, in terms of metabolic rate regulation, was greater at high aerobic migration rates. They swam American shad in a large respirometer at a rate of 1.0 - 2.3 body lengths (BL) s and found that metabolic rates were intermediate between salmonids and fast-swimming perciforms (including tunas) and may be a result of evolutionary adaptation to their active pelagic schooling life history (Leonard et al. 1999). This experimental rate is consistent with the average migration rate (2.0 BL/s) of upriver migrating American shad in my study.

Passage

One of the main approaches used to restore runs of anadromous fishes is to provide access to upriver habitats using fish passage. Methods range from straightforward approaches, such as complete dam removal, to more complex operations like the construction of fishways and fish lifts (Weaver et al. 2003; Sprankle 2005; Burdick and Hightower 2006). The current approach on the Cape Fear River entails using the chambers at each lock and dam to move fish from the lower to upper pool. My data show successful upstream passage of both species through the use of this method.

Passage rates through LD-1 and LD-2 were relatively similar between species; however, American shad showed higher passage rates through LD-3 than striped bass. This could indicate a problem with striped bass passage at LD-3, but might also be linked to the fact that the majority of striped bass eggs were collected from the LD-3 site. Striped bass might forgo migration beyond LD-3 if this section of the river is suitable for spawning. Further investigations are required to better understand this potential link.

The passage rates can be used to estimate the fraction of the spawning population that would be present below each lock and dam and above the three dams. For example, passage estimates for American shad (65, 85, and 64%) suggest that 35% ((1-0.65)*100) of fish would remain below LD-1, 10% (0.65*(1-0.85)*100) would be between LD-1 and LD-2, 20% (0.65*0.85*(1-0.64)*100) would be between LD-2 and LD-3, with the remainder (35%) above LD-3. For striped bass, the predicted distribution is 23% below LD-1, 19% between LD-1 and LD-2, 32% between LD-2 and LD-3, with the remainder (25%) above LD-3. These predicted distributions shares some characteristics with the distributions of collected eggs although both overestimate the proportion of eggs that would be collected above LD-3 (Figure 22). As discussed above, the low percentages of eggs collected from the upper river may be due to sampling inefficiencies.

Overall, passage rates of American shad and striped bass through locks and dams on the Cape Fear River were higher than those seen by other researchers looking at anadromous fish passage. Moser et al. (2000) used sonic telemetry and found rates of passage of American shad at LD-1 on the Cape Fear River to be 38% in 1996, 18% in

1997, and 61% in 1998. Also in 1998, they calculated the passage rate of American shad through LD-2 at 33%. As in my study, these rates of passage were based on fish that remained or returned to the dam after tagging and had potential for passage (N=16 in 1996, N=11 in 1997 and N=36 (LD-1) N=15 (LD-2) in 1998). It is also important to point out that my estimates of passage occurred a decade after the changes in locking procedures aimed at improving fish passage were initiated during the study by Moser et al. (2000). CZR Inc. also used this method for reporting passage rates of both species on the Cape Fear River. They found rates for American shad of 50% in 2002 (N=8), 33% in 2003 (N=12), and 25% in 2004 (N=40); and for striped bass at 0% in 2002 (N=2), 23% in 2003 (N=22), and 61% in 2004 (N=46). In comparison, Bailey et al. (2004) used radio telemetry observations and found rates of passage for American shad returning to New Savannah Bluff Lock and Dam on the Savannah River to be 50% in 2001 and 9% in 2002 (N=30 in 2001 and N=12 in 2002).

The additional receiver placed inside the lock chamber at LD-1 provided interesting data on fish passage. Particularly, three striped bass were detected by the receiver inside the chamber at LD-1 but failed to utilize the lock to move upstream. This is despite the fact that they were detected during times of the day when locking procedures would have been conducted. Similarly, Moser et al. (2000) saw American shad enter the lock chamber at LD-1 on the Cape Fear River but fail to pass upstream. Future investigation should incorporate the use of a receiver inside the chamber at each lock and dam to further understand passage of fish via the locks.

Future Directions

Despite low sample sizes and variability in egg sampling there are some encouraging similarities in results from egg sampling and telemetry. For American shad, the section of the river below LD-1 had the highest egg collections and a tie for the predicted proportion of the run (35%, tied with the upper river). For striped bass, the section below LD-3 had the highest egg collections and highest predicted proportion of the run. Egg collections were lower than expected from the upper river. This is likely due to the fact that lock and dam sites provide sampling of aggregates of fish during peak spawning times and upriver sites do not. Further directed efforts will need to be undertaken in order to better evaluate these differences and provide a more accurate characterization of spawning distribution of anadromous fishes in the Cape Fear River. A possible direction for future research could be more intensive diel tracking of tagged fish to locate potential upriver spawning areas. These locations could then be sampled during the evening hours when spawning activity is more likely to take place. This approach would be logistically challenging due to limited access of the upper sections of the Cape Fear River.

It would also be valuable to estimate the size of the American shad spawning population present in the Cape Fear River. Such estimates have been obtained in other systems through mark-recapture (American shad, Bailey et al. 2004). An estimate for the Cape Fear population, coupled with information about egg densities and passage rates,

could provide a much clearer picture of the impact of the locks and dams on anadromous fish migrations. Further investigations are needed if these questions are to be sufficiently answered.

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Table 1. Coordinates and average Temp, DO, depth, volume of water sampled, and density of stage 1 American shad eggs (eggs/1,000 m^3) collected at each egg sampling location on the Cape Fear River, North Carolina. Averages based on all samples taken at each location from 9 March – 31 May 2007 and 5 March – 4 June 2008.

			Temp (°C)		DO (mg/L)		Depth (m)		Vol. sampled (m^3)		Eggs/1,000m^3	
Site (rkm)	Lat (DD)	Lon (DD)	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Lock & Dam 1 (97)	34.4016	78.2903	18.7	18.3	7.4	8.7	7.0	6.1	67.4	70.7	526	426
Lock & Dam 2 (149)	34.6254	78.5697	18.6	17.9	7.4	8.5	6.5	6.2	50.4	52.0	57	50
Lock & Dam 3 (186)	34.8311	78.8221	18.8	17.6	8.1	8.7	3.6	3.9	58.9	69.9	18	23
Fayetteville (226)	35.1115	78.8557	18.9	17.4	8.1	8.8	4.1	4.1	61.9	68.9	2	2
Lillington (273)	35.3942	78.7656	19.1	17.7	8.4	9.0	1.7	1.8	70.8	51.9	0	0

Table 2. American shad eggs by stage of development collected from five sites sampled March 9 - June 1, 2007 and March 5 – June 4, 2008 on the Cape Fear River, NC. Development criteria from Jones et al. (1978).

	Number of Eggs by Stage of Development											
	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Total # Eggs	
Site (Rkm)	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
LD-1 (97)	466	600	6	4	0	3	2	2	1	1	**474**	**609**
LD-2 (149)	70	57	8	14	1	0	2	2	1	1	**81**	**73**
LD-3 (186)	21	33	8	4	0	6	0	0	0	0	**29**	**43**
Fayetteville (226)	2	3	0	0	0	0	0	0	0	1	**2**	**3**
Lillington (273)	0	0	0	0	0	0	0	0	0	0	**0**	**0**
Total	**559**	**693**	**22**	**22**	**1**	**9**	**4**	**4**	**2**	**3**	**586**	**728**

Table 3. Nominal logistic regression model results for effect of temperature on presence/absence of American shad eggs in plankton net samples from 2007 and 2008 on the Cape Fear River, NC.

Term	Parameter Estimate	Std Error	Prob>ChiSq
Intercept	3.88	1.23	0.002
Temp (C)	-0.23	0.07	0.0005
(Temp (C)-18.5)*(Temp (C)-18.5)	0.08	0.02	<0.0001

Table 4. Regression model results for effects of sample site location, hour bin, and temperature on log-scale density (eggs/1,000m^3) of American shad eggs in plankton net samples from 2007 and 2008 on the Cape Fear River, NC.

Term	Parameter Estimate	Std Error	Prob>|t|
Intercept	-9.92	1.18	<.0001
Location[LD-1]	0.33	0.15	0.03
Location[LD-2]	0.20	0.16	0.23
Hour Bin[17-0]	1.91	1.27	0.14
Hour Bin[18-17]	-0.42	0.92	0.65
Hour Bin[19-18]	0.02	0.55	0.98
Hour Bin[20-19]	1.17	0.32	0.0004
Hour Bin[21-20]	-0.88	0.30	0.004
Hour Bin[22-21]	-0.17	0.42	0.69
Hour Bin[23-22]	-0.16	0.60	0.79
Temp (C)	0.23	0.03	<.0001

Table 5. Striped bass eggs by stage of development collected from five sites sampled March 9 - June 1, 2007 and March 5 – June 4, 2008 on the Cape Fear River, NC. Development criteria provided by Jones et. al. (1978).

	Number of Eggs by Stage of Development											
	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Total # Eggs	
Site (Rkm)	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
LD-1 (97)	0	1	0	0	0	6	0	0	0	0	**0**	**7**
LD-2 (149)	0	3	0	1	0	0	0	0	0	0	**0**	**4**
LD-3 (186)	0	19	0	0	0	10	0	0	0	0	**0**	**29**
Fayetteville (226)	0	0	0	0	0	0	0	1	0	0	**0**	**1**
Lillington (273)	0	0	0	0	0	0	0	0	0	0	**0**	**0**
Total	**0**	**23**	**0**	**1**	**0**	**16**	**0**	**1**	**0**	**0**	**0**	**41**

Table 6. Tag retention experiment conducted on April 4, 2007 at the NC Wildlife Resources Commission's Watha Hatchery. Ten American shad were implanted with VEMCO V9-1L-R04K coded transmitters and an additional 11 were held as controls. Fish were held in a round hatchery tank and observed over a five-day period for mortality and tag expulsion. There were no mortalities among the control fish.

Fish #	Total length (mm)	Sex	Expelled Tag	Mortality
1	465	M	No	3 days after tagging
2	450	M	No	No
3	475	M	No	No
4	425	M	No	No
5	436	M	No	12 hrs after tagging
6	415	M	No	No
7	525	F	No	No
8	426	M	No	No
9	455	M	No	No
10	455	M	No	No

Table 7. Date of release, tag identification number, sex, and total length for American shad implanted with VEMCO V9-1L-R04K coded transmitters during the 2007 field season. Release treatments indicate whether or not fish were held in the instream holding pen or released directly into the river. Duration listed (hours) indicates how long fish were held with the door closed. The total number of fish held is given; tagged fish are identified by (T) and untagged by (U). First receiver detection refers to stationary receivers; fish not detected = ND.

Release Date	Tag ID	Sex	TL (mm)	Release Treatment	First Receiver Detection
4/24/07	2415	M	423	24 hrs, Am. shad: 5(T) 10(U), striped bass: 2(T)	95 Bridge
4/24/07	2418	M	427	24 hrs, Am. shad: 5(T) 10(U), striped bass: 2(T)	301 Bridge
4/24/07	2422	M	451	24 hrs, Am. shad: 5(T) 10(U), striped bass: 2(T)	95 Bridge
4/24/07	2424	M	471	24 hrs, Am. shad: 5(T) 10(U), striped bass: 2(T)	95 Bridge
4/24/07	2426	M	418	24 hrs, Am. shad: 5(T) 10(U), striped bass: 2(T)	95 Bridge
5/3/07	2430	M	482	4 hrs, Am. shad: 5(T) 6(U)	301 Bridge
5/3/07	2431	F	509	4 hrs, Am. shad: 5(T) 6(U)	301 Bridge
5/3/07	2432	M	432	4 hrs, Am. shad: 5(T) 6(U)	95 Bridge
5/3/07	2433	F	513	4 hrs, Am. shad: 5(T) 6(U)	95 Bridge
5/3/07	2434	F	482	4 hrs, Am. shad: 5(T) 6(U)	301 Bridge
5/9/07	2416	F	473	Door left open, Am. shad: 7(T), leave at will	95 Bridge
5/9/07	2417	F	477	Door left open, Am. shad: 7(T), leave at will	301 Bridge
5/9/07	2419	F	540	Door left open, Am. shad: 7(T), leave at will	95 Bridge
5/9/07	2420	F	529	Door left open, Am. shad: 7(T), leave at will	95 Bridge
5/9/07	2421	F	512	Door left open, Am. shad: 7(T), leave at will	ND
5/9/07	2423	F	518	Door left open, Am. shad: 7(T), leave at will	ND
5/9/07	2425	F	487	Door left open, Am. shad: 7(T), leave at will	301 Bridge
5/14/07	2427	M	415	Directly into river, no pen.	301 Bridge
5/14/07	2428	F	500	Directly into river, no pen.	301 Bridge
5/14/07	2429	F	500	Directly into river, no pen.	301 Bridge

Table 8 Date of release, tag identification number, sex, total length, and total time spent in surgery for striped bass implanted with VEMCO V13-1L-R64K coded transmitters during the 2007 field season. Release treatments indicate whether or not fish were held in the instream holding pen or released directly into the river. Duration listed (hours) indicates how long fish were held with the door closed. The total number of fish held is given; tagged fish are identified by (T) and untagged by (U). First receiver detection refers to stationary receivers; fish not detected = ND.

Release Date	Tag ID	Sex	TL (mm)	Surgery Time (min)	Release Treatment	First Receiver Detection
4/13/07	3269	M	515	15	Directly into river, no pen.	95 Bridge
4/13/07	3270	M	796	17	Directly into river, no pen.	95 Bridge
4/13/07	3271	F	792	15	Directly into river, no pen.	95 Bridge
4/13/07	3272	F	754	10	Directly into river, no pen.	95 Bridge
4/13/07	3273	M	559	11	Directly into river, no pen.	95 Bridge
4/13/07	3274	M	761	11	Directly into river, no pen.	95 Bridge
4/24/07	3275	M	589	13	24 hrs, striped bass:2(T), Am. shad:5(T) 10(U)	95 Bridge
4/24/07	3276	M	586	12	24 hrs, striped bass:2(T), Am. shad:5(T) 10(U)	95 Bridge
5/7/07	3277	M	803	8	Directly into river, no pen.	95 Bridge
5/7/07	3278	F	838	8	Directly into river, no pen.	95 Bridge
5/7/07	3279	M	577	10	Directly into river, no pen.	95 Bridge
5/7/07	3280	M	665	7	Directly into river, no pen.	95 Bridge
5/7/07	3281	M	571	7	Directly into river, no pen.	95 Bridge
5/7/07	3282	F	613	13	Directly into river, no pen.	95 Bridge
5/7/07	3283	M	710	8	Directly into river, no pen.	95 Bridge
5/7/07	3284	M	567	11	Directly into river, no pen.	95 Bridge
5/7/07	3285	M	636	6	Directly into river, no pen.	95 Bridge
5/7/07	3286	M	585	7	Directly into river, no pen.	ND
5/7/07	3287	M	560	6	Directly into river, no pen.	95 Bridge
5/7/07	3288	M	538	7	Directly into river, no pen.	95 Bridge

Table 9. Date of release, tag identification number, sex, and total length for American shad implanted with VEMCO V9-1L-R04K coded transmitters during the 2008 field season. Last column denotes whether or not fish moved upstream of Lock and Dam 1 after release.

Release Date	Tag ID	Sex	TL	Capture Method	Moved Upstream of LD-1 (rkm97)
3/13/08	10264	M	470	Electrofishing	N
3/18/08	10263	M	440	Electrofishing	Y
3/18/08	10262	M	425	Electrofishing	N
3/18/08	10261	M	405	Electrofishing	N
3/18/08	10260	M	450	Electrofishing	N
3/18/08	10259	M	395	Electrofishing	N
3/18/08	10258	M	405	Electrofishing	Y
3/18/08	10257	M	435	Electrofishing	N
3/20/08	10251	M	390	Hook and Line	Y
3/20/08	10252	M	407	Hook and Line	N
3/25/08	10253	M	419	Hook and Line	Y
3/25/08	10254	M	400	Hook and Line	Y
3/25/08	10255	M	435	Hook and Line	Y
3/25/08	10245	M	440	Hook and Line	Y
3/25/08	10246	M	442	Hook and Line	Y
3/25/08	10247	M	415	Hook and Line	Y
3/25/08	10248	M	460	Hook and Line	Y
3/25/08	10249	F	505	Hook and Line	Y
3/25/08	10250	M	421	Hook and Line	Y
3/25/08	10255	M	452	Hook and Line	Y

Table 10. Date of release, tag identification number, sex, total length, and time spent in surgery for striped bass implanted with VEMCO V13-1L-R64K coded transmitters during the 2008 field season. Last column denotes whether or not fish moved upstream of Lock and Dam 1 after release. ** Fish 10231 and 10232 were caught and released below Lock and Dam 2 (rkm 149).

Date	Tag ID	Sex	TL (mm)	Surgery Time (min)	Moved Upstream of LD-1 (rkm97)
2/26/08	10243	M	574	7	N
2/26/08	10244	M	500	6	N
3/10/08	10242	M	536	8	N
3/18/08	10241	M	520	19	Y
3/18/08	10240	F	858	9	N
3/18/08	10235	M	596	6	N
3/27/08	10236	M	639	11	Y
4/10/08	10237	M	724	9	Y
4/10/08	10239	F	720	6	N
4/10/08	10238	M	692	7	Y
4/10/08	10230	M	571	5	Y
4/10/08	10232	F	742	6	**
4/10/08	10231	M	591	5	**
4/15/08	10234	M	672	4	Y
4/16/08	10233	M	740	4	Y
4/16/08	10225	M	602	5	Y
4/21/08	10226	M	790	4	Y
4/21/08	10227	M	710	6	Y
4/21/08	10228	M	630	6	N
4/21/08	10229	F	705	5	N

Table 11. Multiple regression model results for effects of starting location (start rkm) and streamflow on migration rate of sonic-tagged American shad, based on stationary receiver detections from 2007 and 2008 in the Cape Fear River, NC.

Term	Parameter Estimate	Std Error	Prob>|t|
Intercept	1.47	0.32	<0.0001
Start rkm[149-97]	-0.35	0.45	0.43
Start rkm[186-149]	1.85	0.47	0.0003
Start rkm[212-186]	-1.13	0.40	0.007
Start rkm[220-212]	-0.24	0.34	0.50
Start rkm[231-220]	-0.24	0.47	0.60
Start rkm[246-231]	-0.11	0.70	0.88
Start rkm[261-246]	0.28	0.80	0.73
Median Flow (m3s)	0.009	0.001	<0.0001

Table 12. Multiple regression model results for effects of starting location (start rkm) and streamflow on migration rate of sonically tagged striped bass, based on calculations from stationary receiver detection data from 2007 and 2008 in the Cape Fear River, NC.

Term	Parameter Estimate	Std Error	Prob>|t|
Intercept	2.0494922	0.455975	0.0001
Start rkm[149-97]	-0.09057	0.455079	0.8439
Start rkm[186-149]	1.8082843	0.560342	0.0035
Start rkm[212-186]	-1.10529	0.562137	0.0605
Start rkm[220-212]	0.5039364	0.546312	0.3651
Start rkm[231-220]	-1.472546	0.578855	0.0175
Start rkm[246-231]	0.1143599	0.987783	0.9088
Start rkm[261-246]	0.1960192	1.189461	0.8704
Median Flow (m3sec)	0.0057475	0.003266	0.0907

Table 13. Published reports of range of temperatures (C°) over which peak American shad spawning occurs.

Publication	River(s)	Peak Temp. Range (°C)
Walburg and Nichols 1967	Multiple (Atlantic)	14-21
Leggett and Whitney 1972	Multiple (Pacific, Atlantic)	15-24
Klauda et al. 1991	Chesapeake Bay Tribs.	12-21
Ross et al. 1993	Delaware	15-25
Sparks and Hightower 1998	Roanoke	20-23
Burdick and Hightower 2006	Neuse	18-20
Smith and Rulifson 2006	Tar	16-24
This Study	Cape Fear	18-22

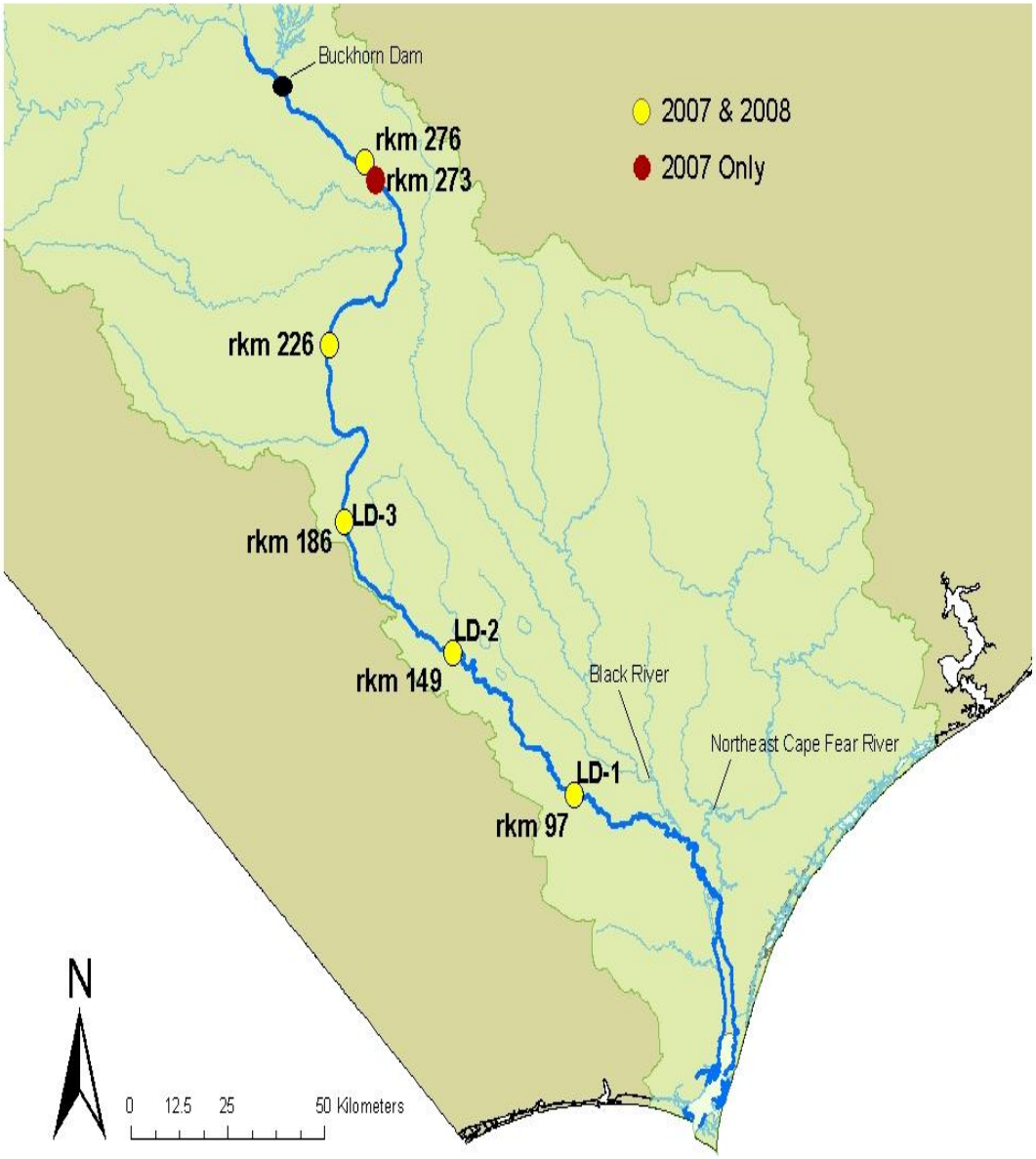


Figure 1. Location and associated river km of egg sampling stations within the Cape Fear river during the 2007 and 2008 field seasons. Locks and dams are shown for reference.

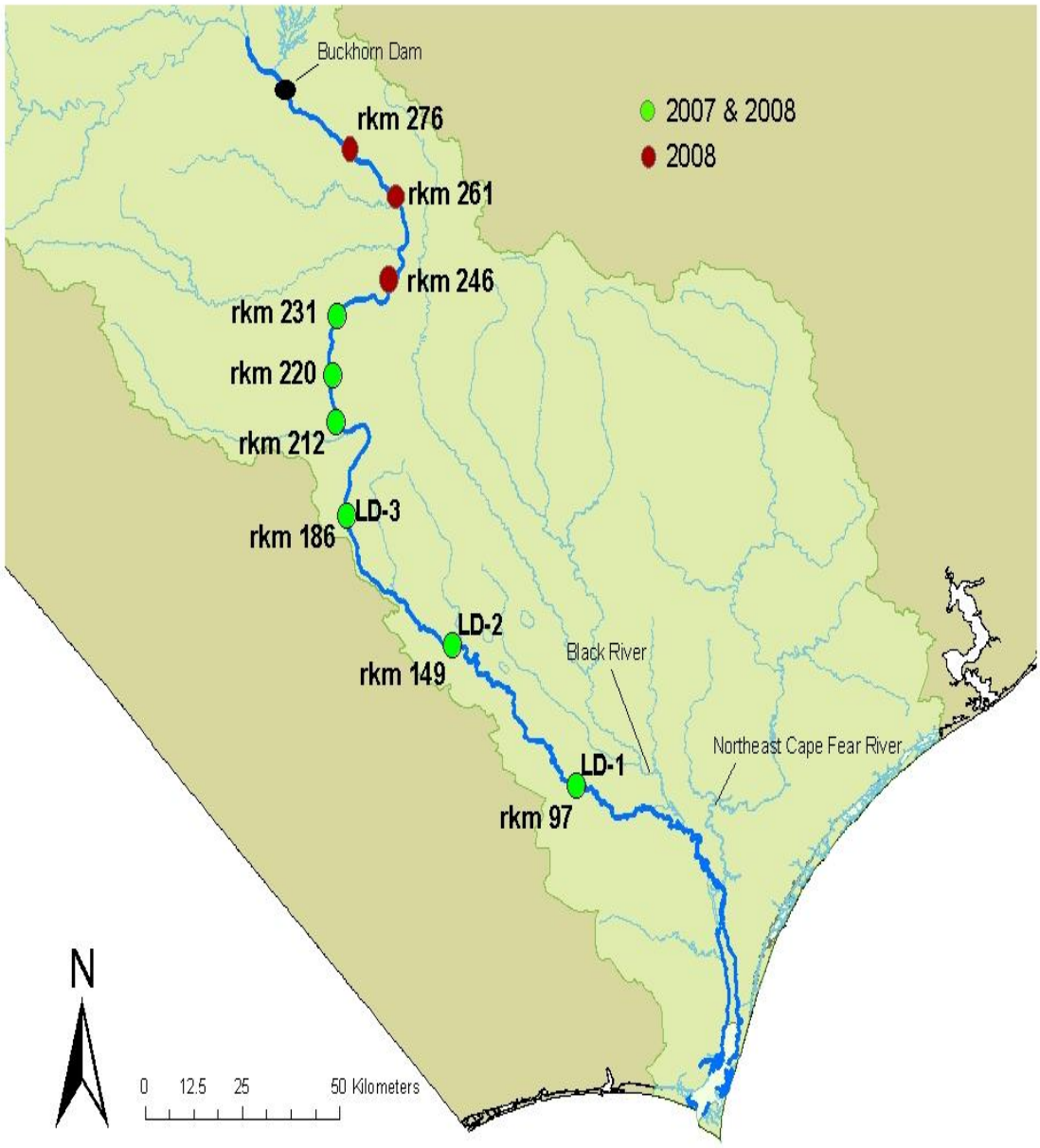


Figure 2. Location and associated river km of stationary receivers within the Cape Fear River during the 2007 and 2008 field seasons. Locks and dams are shown for reference.

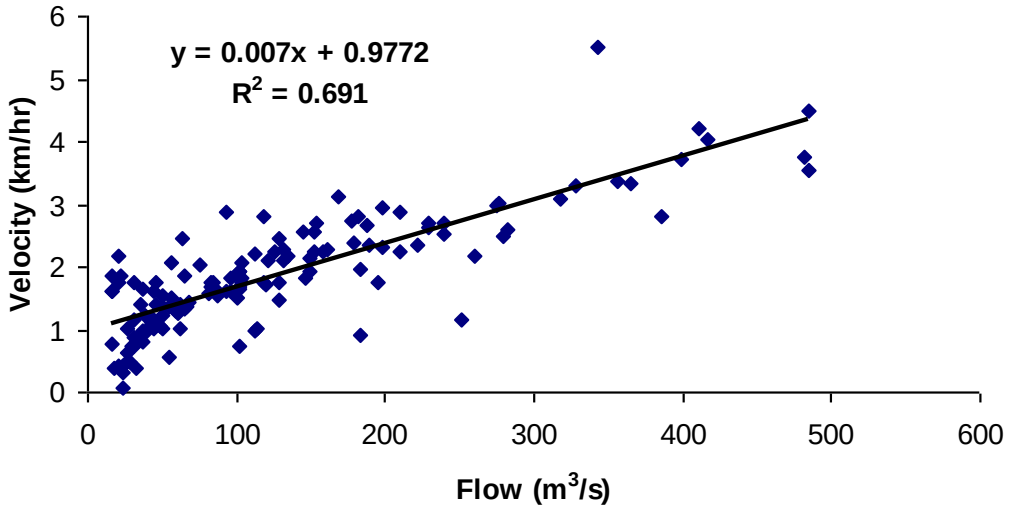


Figure 3. Linear fit of streamflow (m^3/s) and water velocity (km/hr) measurements from the Cape Fear River, NC.

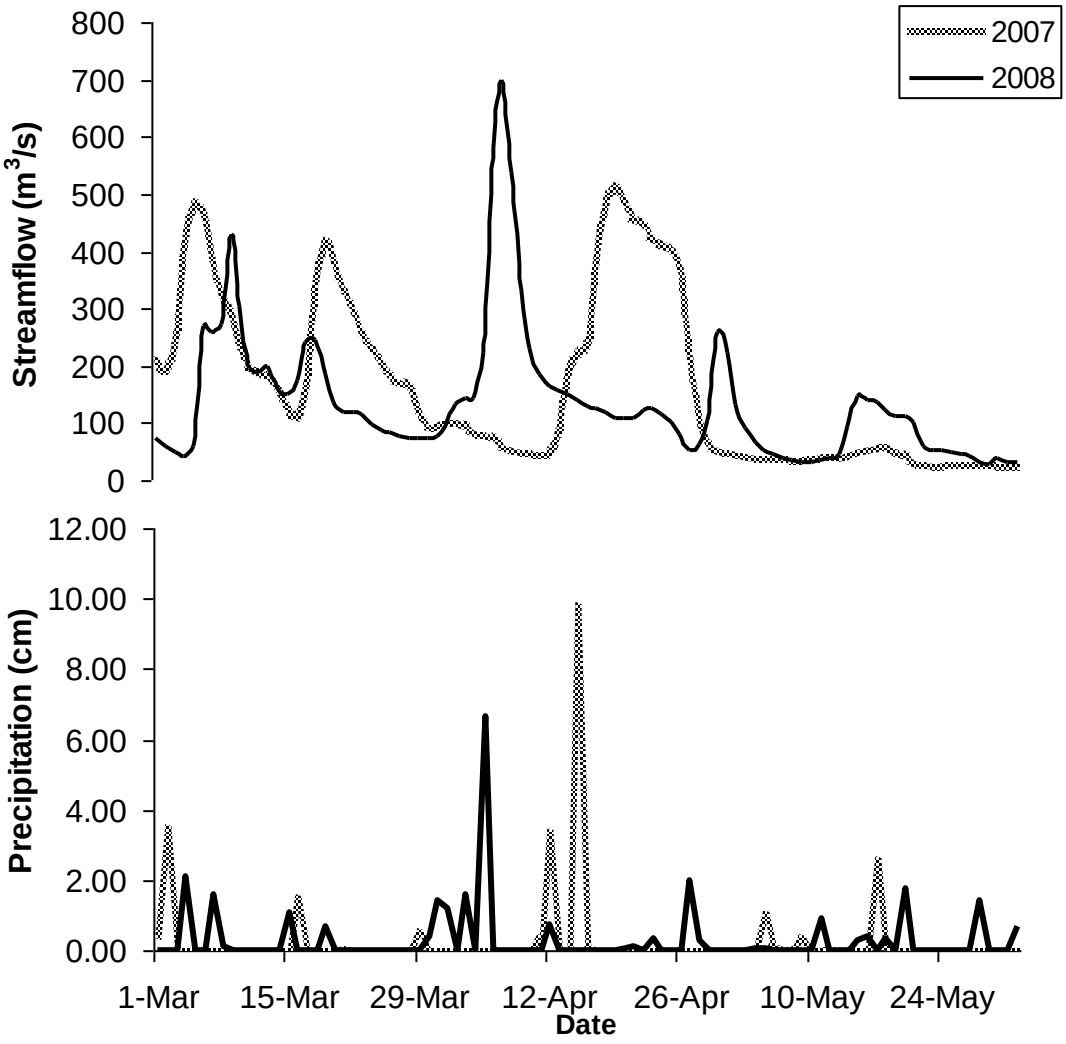


Figure 4. Average daily streamflow (m^3/s) and precipitation data from March 1 to June 1, 2007 and 2008 from the USGS gauge at LD-1 on the Cape Fear River.

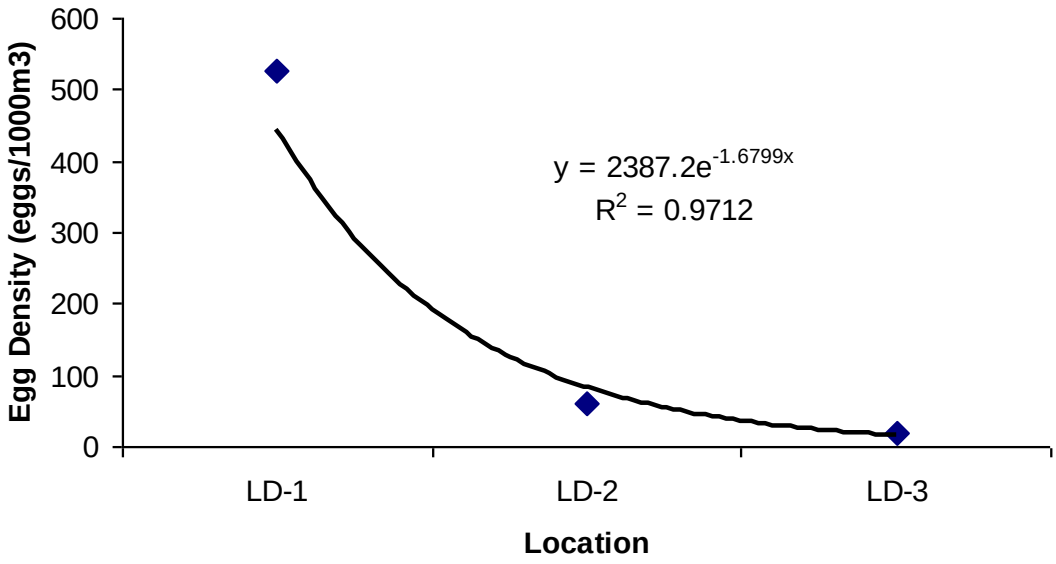


Figure 5. Density of stage-1 American shad eggs (number/1000 m^3) collected from each sampling station on the Cape Fear River, March 5-June 5, 2007. The line is an exponential model fitted using least squares regression.

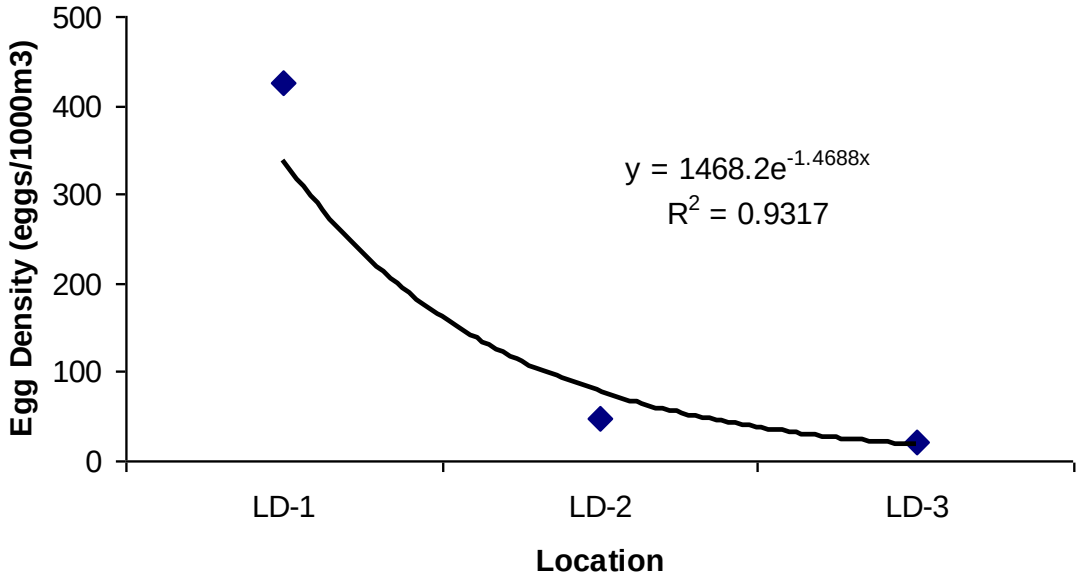


Figure 6. Density of stage-1 American shad eggs (number/1000 m^3) collected from each sampling station on the Cape Fear River, March 5-June 5, 2008. The line is an exponential model fitted using least squares regression.

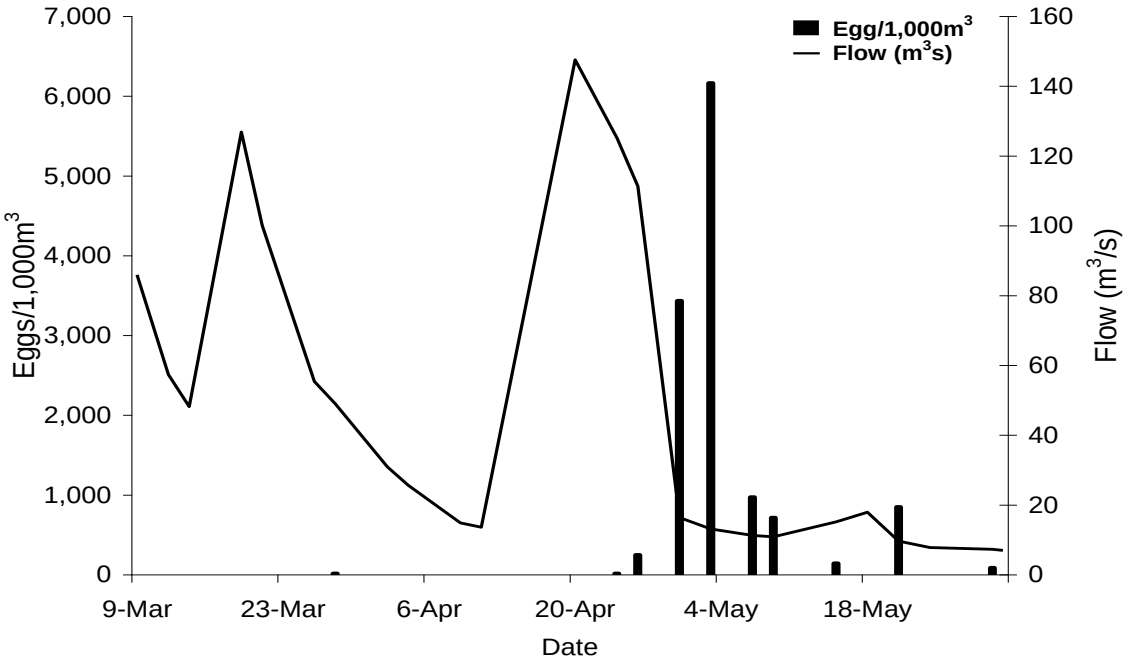


Figure 7. Density (eggs/1000 m^3) of American shad eggs and streamflow (m^3/s) for samples below lock and dam 1 (rkm 97) on the Cape Fear River during the 2007 field season.

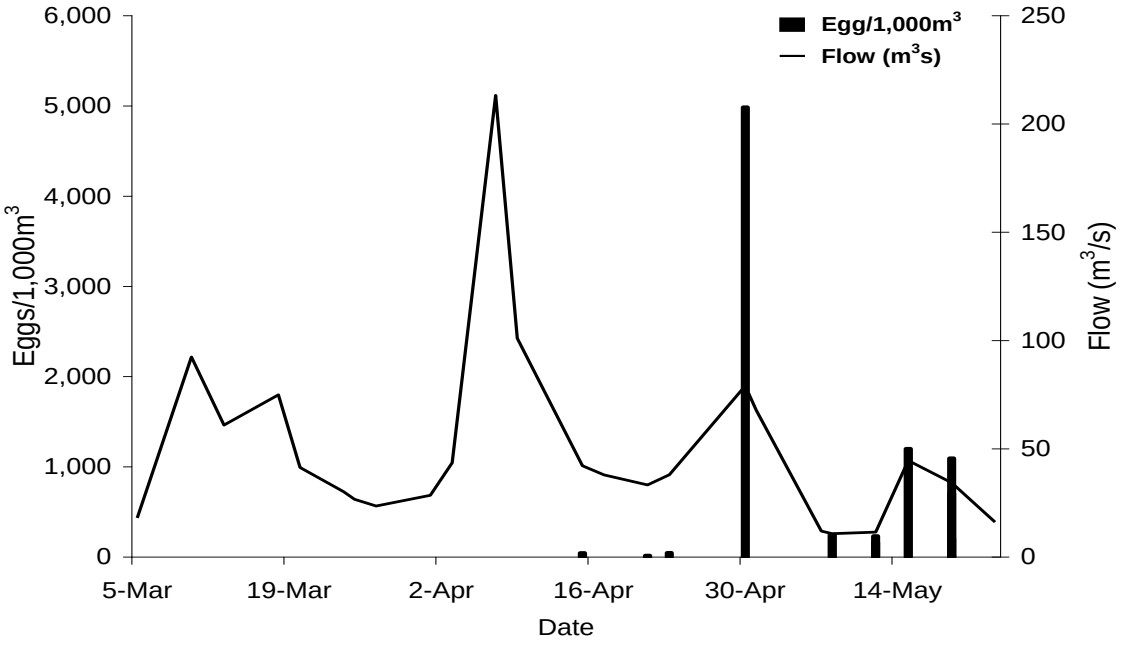


Figure 8. Density (eggs/1000 m^3) of American shad eggs and streamflow (m^3/s) for samples below lock and dam 1 (rkm 97) on the Cape Fear River during the 2008 field season.

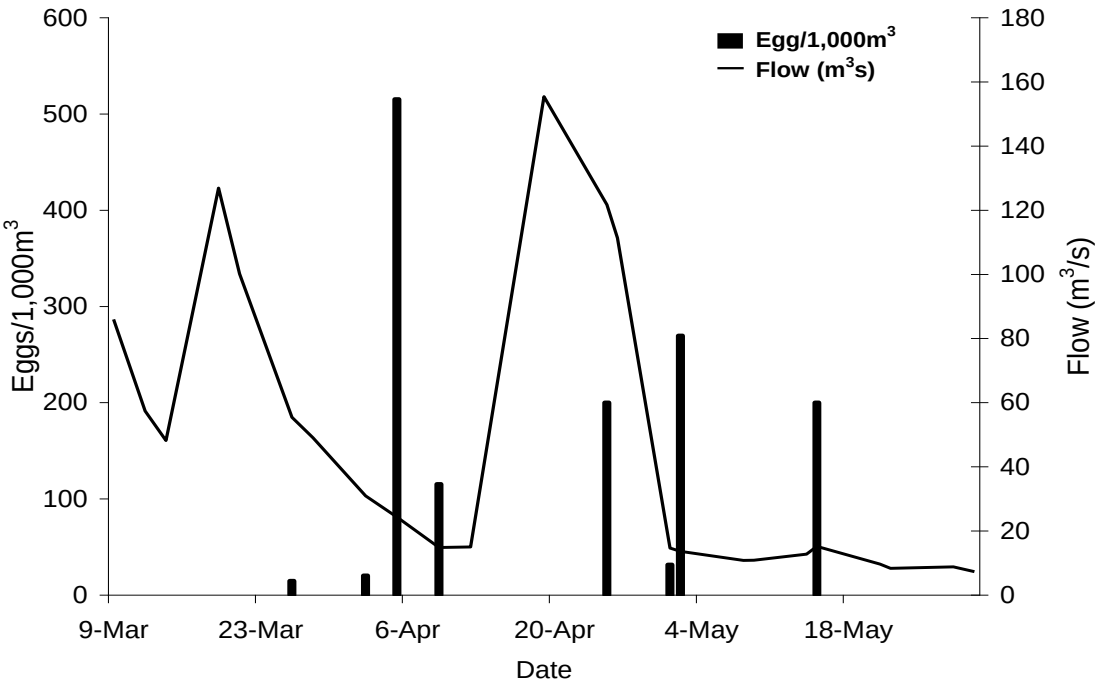


Figure 9. Density (eggs/1000m^3) of American shad eggs and streamflow (m^3/s) for samples below lock and dam 2 (rkm 149) on the Cape Fear River during the 2007 field season.

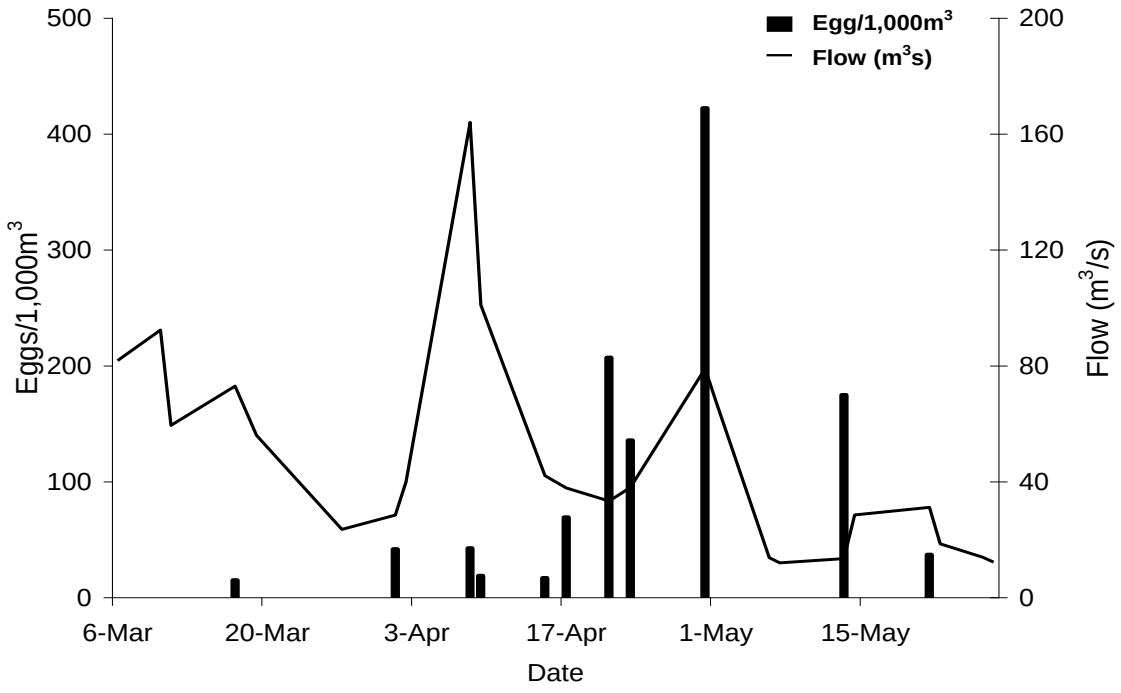


Figure 10. Density (eggs/1000m^3) of American shad eggs and streamflow (m^3/s) for samples below lock and dam 2 (rkm 149) on the Cape Fear River during the 2008 field season.

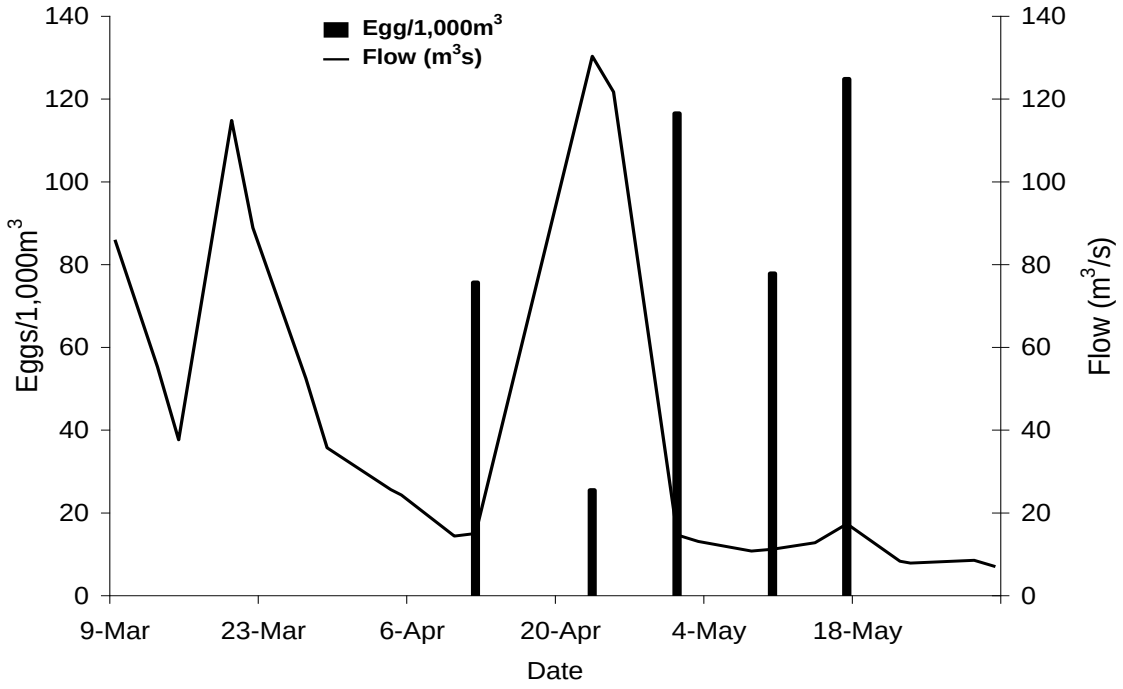


Figure 11. Density (eggs/1000m^3) of American shad eggs and streamflow (m^3/s) for samples below lock and dam 3 (rkm 186) on the Cape Fear River during the 2007 field season.

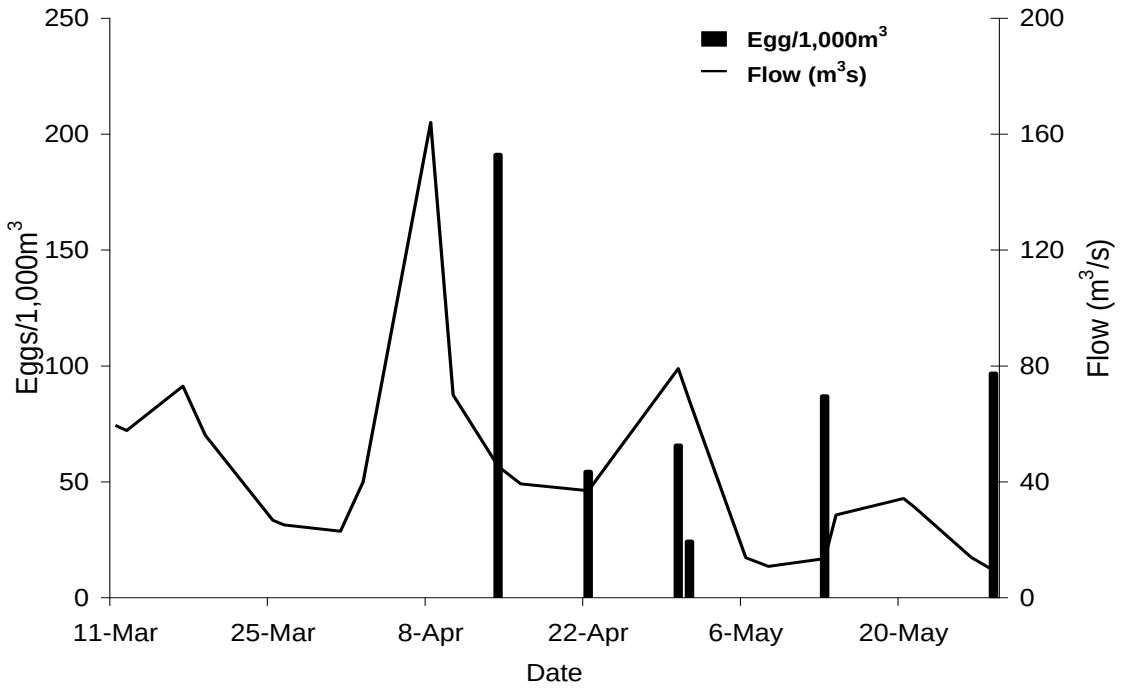


Figure 12. Density (eggs/1000m^3) of American shad eggs and streamflow (m^3/s) for samples below lock and dam 3 (rkm 186) on the Cape Fear River during the 2008 field season.

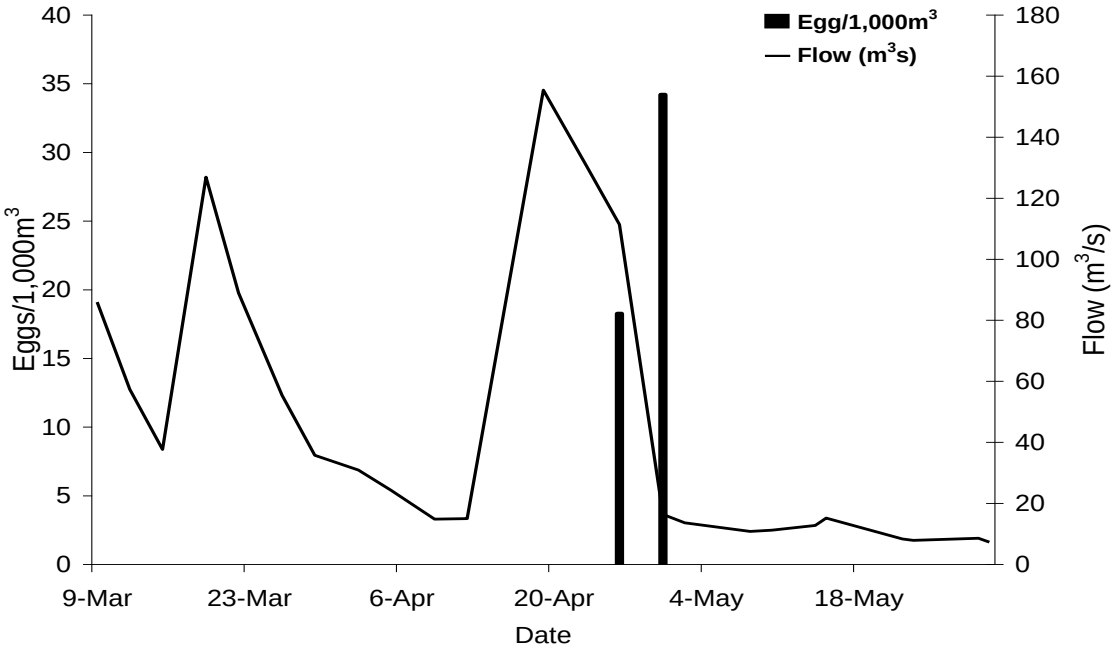


Figure 13. Density (eggs/1000m^3) of American shad eggs and streamflow (m^3/s) for samples near Fayetteville, NC (rkm 226) on the Cape Fear River during the 2007 field season.

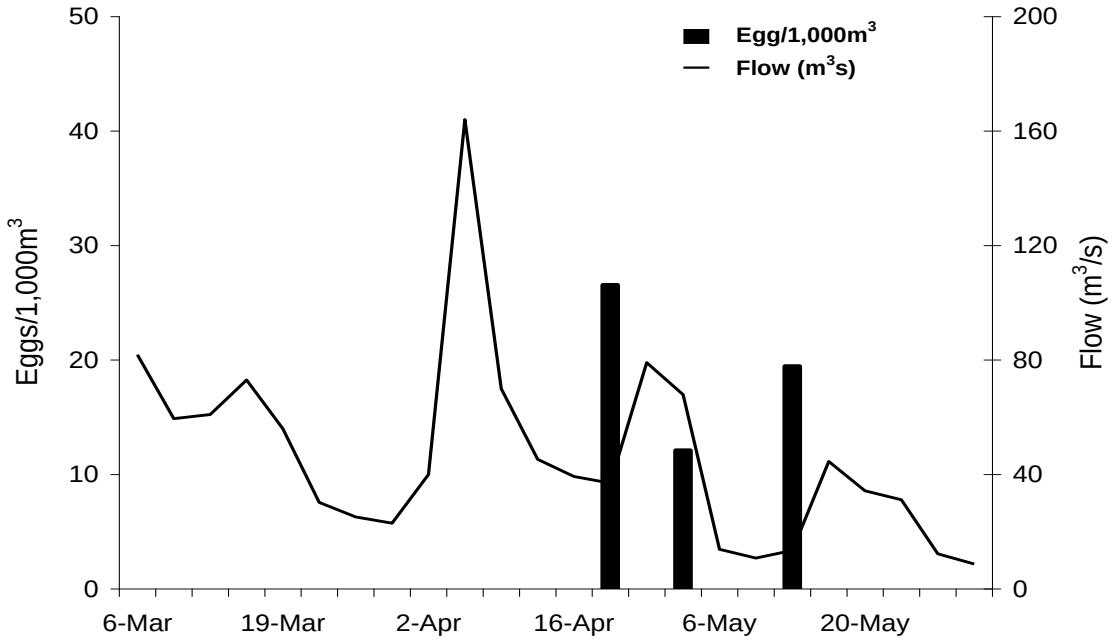


Figure 14. Density (eggs/1000m^3) of American shad eggs and streamflow (m^3/s) for samples near Fayetteville, NC (rkm 226) on the Cape Fear River during the 2008 field season.

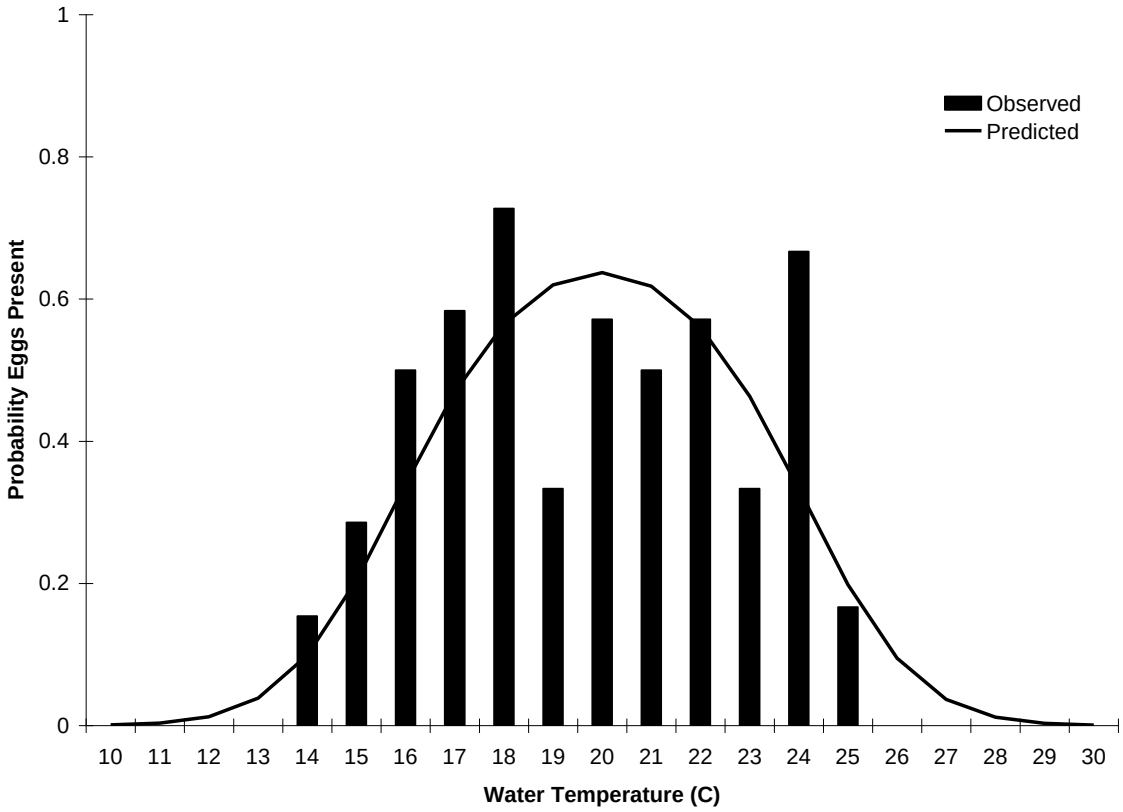


Figure 15. Logistic regression analysis showing water temperature effect on probability of American shad egg presence in plankton net samples based on observed (bars) and predicted (line) values during 2007 and 2008 in the Cape Fear River, NC.

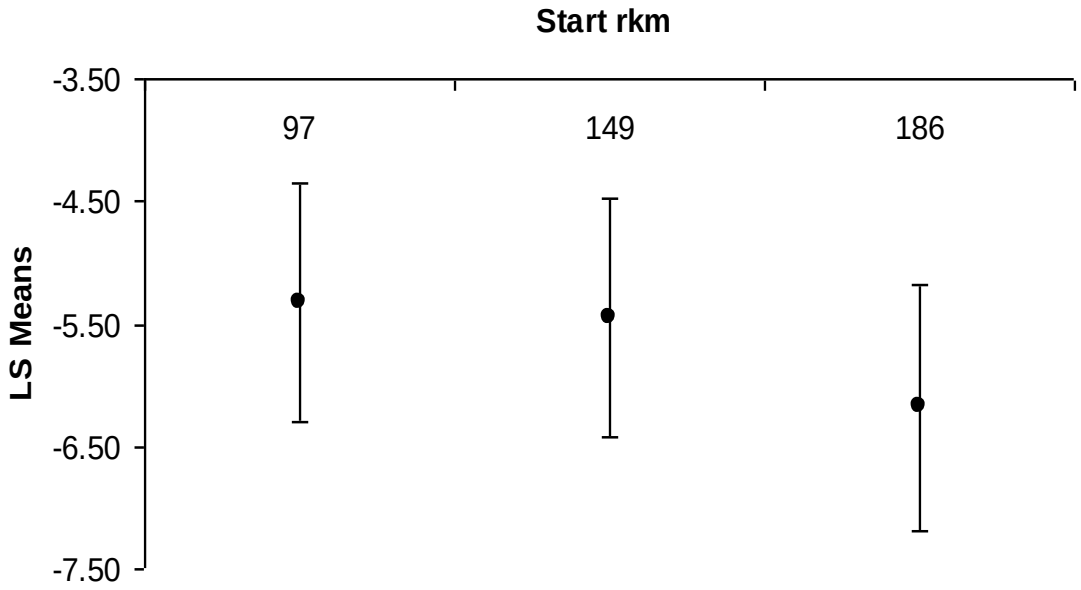


Figure 16. Estimated least square means of log transformed egg densities for the three lock and dams, based on a multiple regression model incorporating location, sampling time and water temperature.

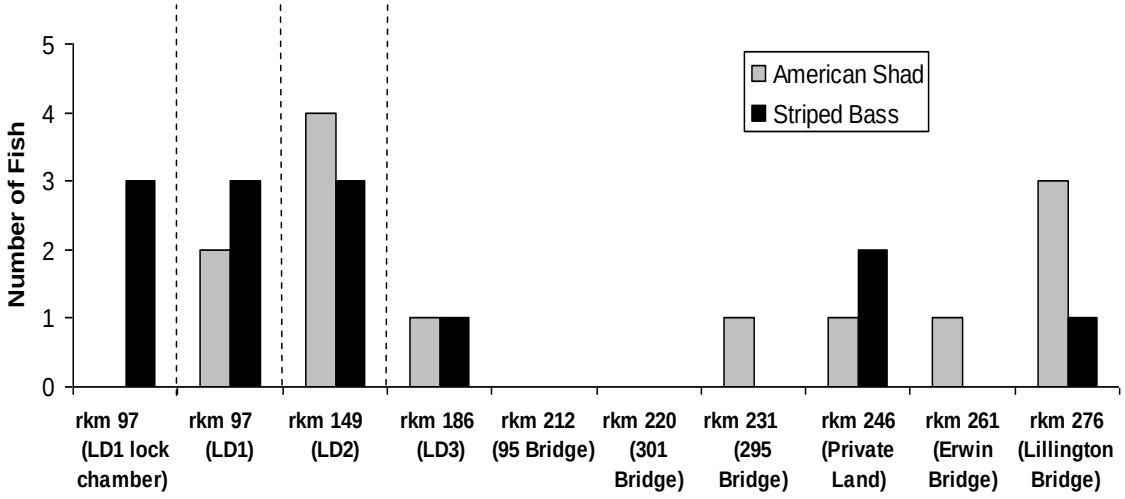


Figure 17. Minimum extent of upstream migration by American shad and striped bass, based on stationary receiver detections in 2008. The X axis shows river kilometer and location of receivers. The Y axis gives number of fish that migrated at least as far upstream as the associated rkm. For example, rkm 246 was the known minimum upriver migration for 2 striped bass and 1 American shad. These fish were detected by other downstream receivers but not by any receivers further upstream of rkm 246. The dashed line represents the dam at Lock and Dam 1. The first receiver (rkm 97) was located inside of the lock chamber at Lock and Dam 1 and fish only detected here (3 striped bass) were not successful in migrating upstream of the dam.

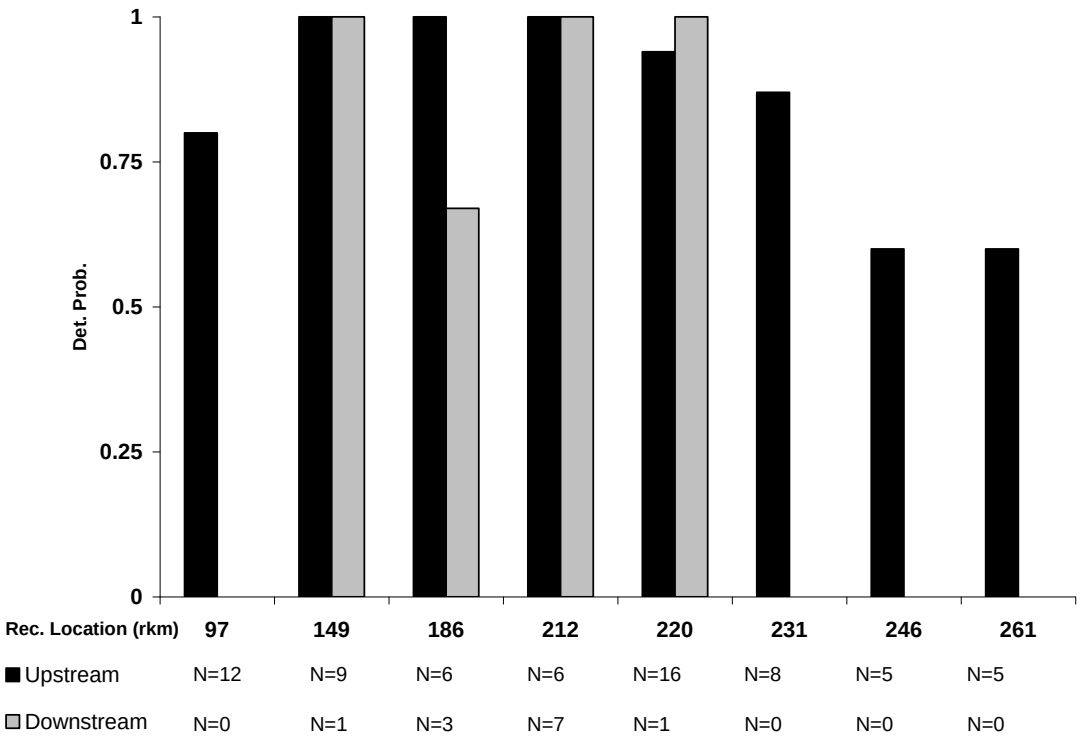


Figure 18. Detection probability of stationary receivers for tagged American shad movements in 2007-2008 on the Cape Fear River, NC. N = number of fish used in calculation.

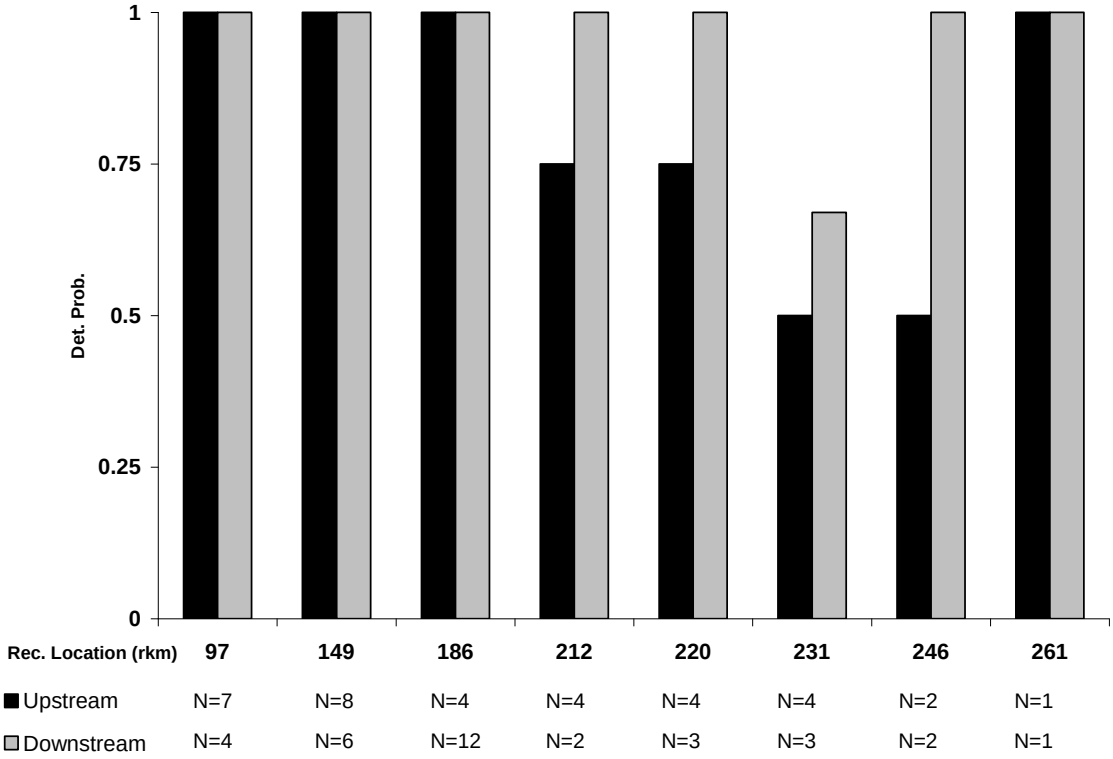


Figure 19. Detection probability of stationary receivers for tagged striped bass movements in 2007-2008 on the Cape Fear River, NC. N = number of fish used in calculation.

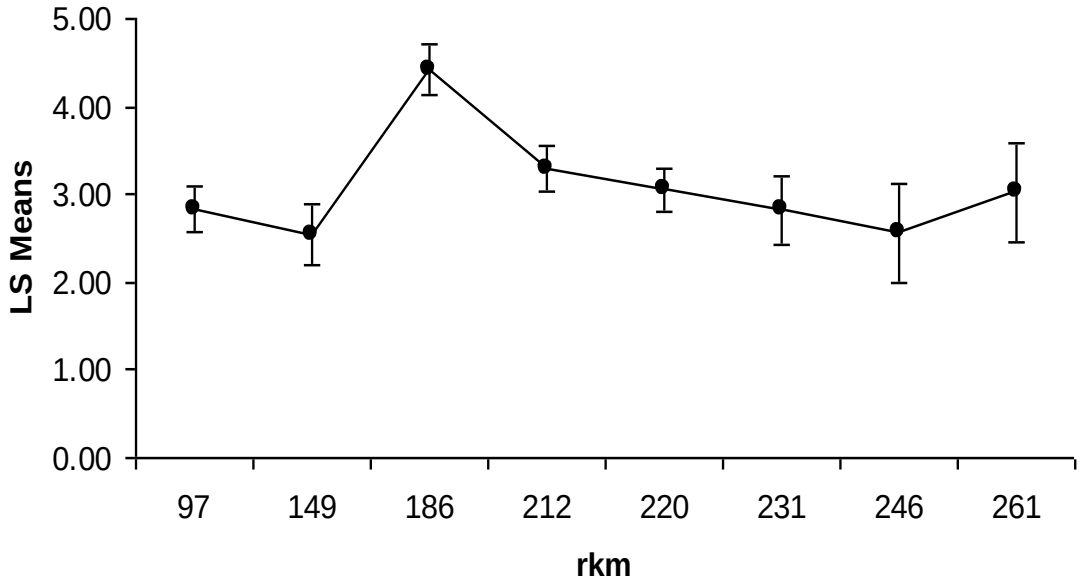


Figure 20. Plot of migration rate least square means values at each start rkm for tagged American shad migrating in the Cape Fear River, NC from 2007-2008.

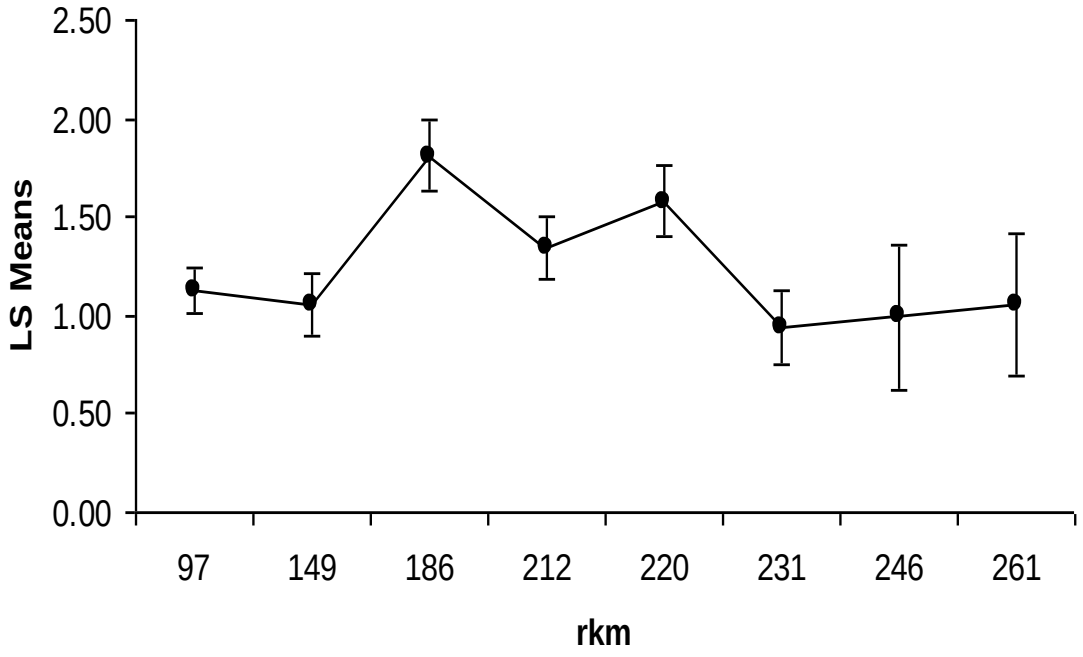


Figure 21. Plot of migration rate least square means values at each start rkm for tagged striped bass migrating in the Cape Fear River, NC from 2007-2008.

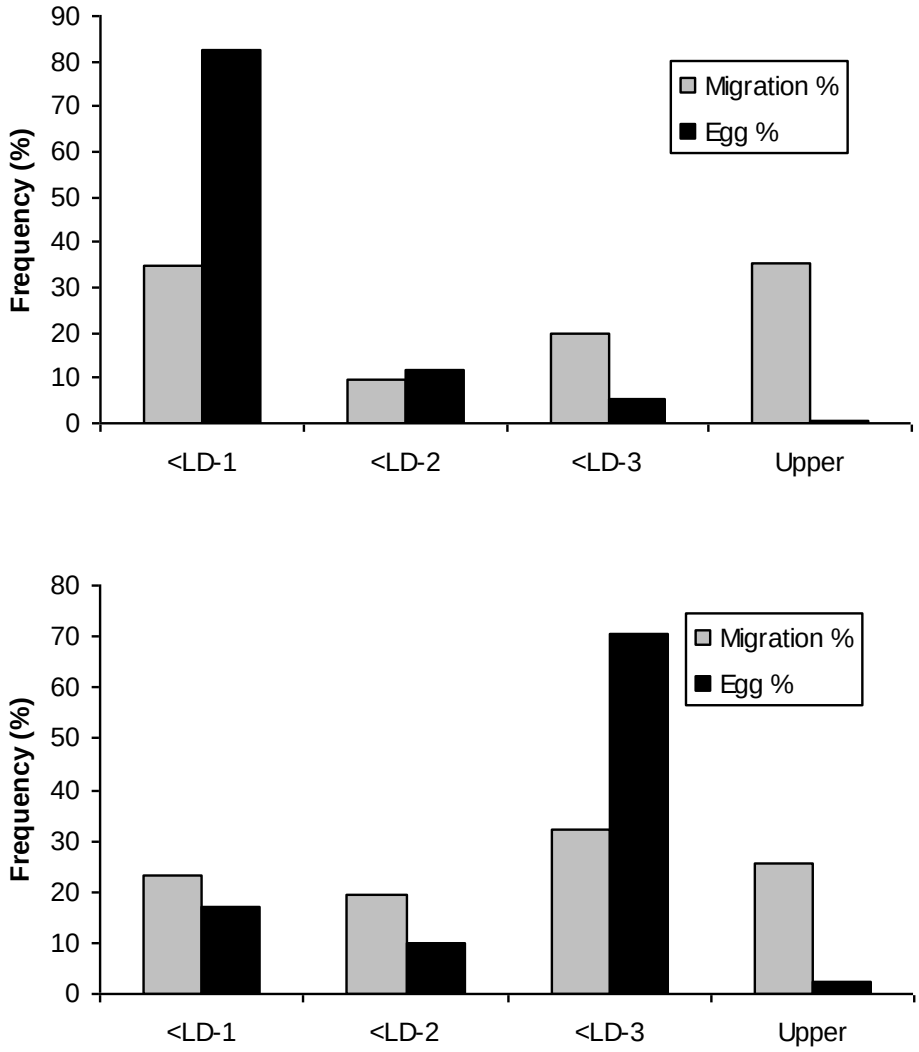


Figure 22. Estimated distribution of spawning adults (Migr %) and observed distribution of collected eggs (Egg %) for American shad (upper panel) and striped bass (lower panel).

APPENDICES

Appendix A Table 1. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species in samples taken at Lock and Dam 1 (rkm 97) on the Cape Fear River in 2007.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/9/07	11.7	9.37	92.12	0	0	0	0	0	0
3/12/07	12.1	9.41	93.86	0	0	0	0	0	0
3/14/07	13.2	9.4	79.62	0	0	0	0	0	0
3/19/07	12.2	8.21	142.73	0	0	0	0	0	0
3/21/07	12.3	8.39	116.70	0	0	0	0	0	0
3/26/07	16.3	7.13	99.15	0	0	0	0	0	0
3/28/07	17.9	8.75	80.43	1	0	0	0	0	0
4/2/07	18.6	8.43	67.83	0	0	0	0	0	0
4/4/07	19.2	8.01	61.73	0	0	0	0	0	0
4/9/07	17.3	7.83	37.17	0	0	0	0	0	0
4/11/07	16.7	7.79	35.53	0	0	0	0	0	0
4/20/07	15.6	7.39	159.25	0	0	0	0	0	0
4/24/07	17.1	7.93	149.33	2	0	0	0	0	1
4/26/07	18.7	6.78	130.42	32	0	0	0	0	1
4/30/07	20.5	5.16	27.98	96	0	0	0	0	1
5/3/07	22.4	6.71	40.90	252	0	0	0	0	1
5/7/07	21.6	6.5	35.05	34	0	0	0	0	0
5/9/07	21.6	6.5	29.49	21	0	0	0	0	0
5/15/07	22.4	6.23	35.34	5	1	0	0	0	2
5/18/07	22.2	6.15	46.36	0	0	0	0	0	1
5/21/07	24.1	6.63	25.95	22	0	0	0	1	0
5/24/07	24	6.1	16.43	0	1	0	0	0	1
5/30/07	25.4	6.82	11.71	1	4	0	0	0	0
5/31/07	25.6	7.05	2.84	0	0	0	0	0	0

Appendix A Table 2. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species in samples taken at Lock and Dam 2 (rkm 149) on the Cape Fear River in 2007.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/9/07	11.5	9.34	81.63	0	0	0	0	0	0
3/12/07	12.4	9.47	74.01	0	0	0	0	0	0
3/14/07	13.5	9.2	56.94	0	0	0	0	0	0
3/19/07	11.3	8.08	102.97	0	0	0	0	0	0
3/21/07	12.1	8.31	90.28	0	0	0	0	0	0
3/26/07	16.7	7.14	68.25	1	0	0	0	0	0
3/28/07	17.8	8.67	56.52	0	0	0	0	0	0
4/2/07	18.3	8.46	49.89	1	0	0	0	0	0
4/5/07	19.4	7.98	46.60	24	0	0	0	0	0
4/9/07	16.8	8.14	43.43	5	0	0	0	0	0
4/12/07	15.9	8.66	44.41	0	0	0	0	0	0
4/19/07	15.3	7.45	121.02	0	0	0	0	0	0
4/25/07	18.1	6.85	110.04	22	0	0	0	0	5
4/26/07	0	0	0.00	0	0	0	0	0	0
5/1/07	21.9	7.2	31.79	1	0	0	0	5	0
5/2/07	22.7	7.25	29.69	8	0	0	0	0	6
5/8/07	21.1	6.5	29.36	0	0	0	0	0	0
5/9/07	21.4	6.76	27.00	0	0	0	0	0	0
5/14/07	21.6	6.69	32.86	0	0	0	0	0	0
5/15/07	22.2	6.6	40.02	8	0	0	0	0	2
5/21/07	23.7	0	24.07	0	0	0	0	0	0
5/22/07	23.8	6.5	20.54	0	0	0	0	0	1
5/28/07	25	7.15	11.35	0	5	0	0	0	0
5/30/07	25.5	7.01	17.65	0	5	0	0	0	0

Appendix A Table 3. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species in samples taken at Lock and Dam 3 (rkm 186) on the Cape Fear River in 2007.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/9/07	11.2	9.64	79.86	0	0	0	0	0	0
3/13/07	13	9.52	64.88	0	0	0	0	0	0
3/15/07	14.3	9.01	53.90	0	0	0	0	0	0
3/20/07	11.4	8.54	106.63	0	0	0	0	0	0
3/22/07	13.7	8.16	92.53	0	0	0	0	0	0
3/27/07	17	7.34	78.81	0	0	0	0	0	0
3/29/07	17.3	8.58	57.50	0	0	0	0	0	0
4/4/07	19.9	7.77	59.69	0	0	0	0	0	0
4/5/07	20	7.57	55.47	0	0	0	0	0	0
4/10/07	14.8	9.43	47.98	0	0	0	0	0	0
4/12/07	14.8	9.22	66.12	5	0	0	0	0	0
4/23/07	17.2	8.35	117.89	3	0	0	0	0	1
4/25/07	18.1	7.45	119.60	0	0	0	0	0	1
5/1/07	22.3	0	34.34	4	0	0	0	0	27
5/3/07	23.1	7.3	32.78	0	0	0	0	0	0
5/8/07	19.9	7.77	39.62	0	0	0	0	0	0
5/10/07	20.4	7.77	38.57	3	0	0	0	0	0
5/14/07	22.2	7.47	48.81	0	0	0	0	0	2
5/17/07	23.2	6.06	48.08	6	0	0	0	0	1
5/22/07	23.7	8.04	31.48	0	0	0	0	0	2
5/23/07	23.5	7.73	31.08	0	0	0	0	0	7
5/29/07	25.2	6.98	26.34	0	0	0	0	0	0
5/31/07	25.9	7.62	22.56	0	0	0	0	0	0

Appendix A Table 4. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species for samples taken in Fayetteville, NC (rkm 226) on the Cape Fear River in 2007.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/9/07	11.1	9.8	86.46	0	0	0	0	0	0
3/12/07	12.4	9.41	81.58	0	0	0	0	0	0
3/15/07	15.5	8.75	55.77	0	0	0	0	0	0
3/19/07	10.7	8.65	94.96	0	0	0	0	0	0
3/22/07	13.5	8.2	106.58	0	0	0	0	0	0
3/26/07	16.7	7.38	173.34	0	0	0	0	0	0
3/29/07	17.7	8.16	69.26	0	0	0	0	0	0
4/2/07	18.7	8.15	67.34	0	0	0	0	0	0
4/5/07	20.1	7.75	54.16	0	0	0	0	0	0
4/9/07	13.9	9.12	41.45	0	0	0	0	0	0
4/12/07	15.9	8.84	48.20	0	0	0	0	0	0
4/19/07	14.7	8.82	131.74	0	0	0	0	2	0
4/23/07	17.2	7.76	129.89	0	0	0	0	0	0
4/26/07	19.5	6.89	54.81	1	0	0	0	0	3
4/30/07	22.5	6.41	29.25	1	0	0	0	0	0
5/2/07	24	6.7	33.26	0	0	0	0	0	0
5/8/07	19	7.57	25.98	0	0	0	0	0	0
5/10/07	22	7.45	32.00	0	0	0	0	0	0
5/14/07	23.8	6.36	40.54	0	0	0	0	0	1
5/15/07	21.9	6.62	45.51	0	0	0	0	0	7
5/22/07	23.9	8.35	20.51	0	0	0	0	0	0
5/23/07	24	8.23	36.27	0	0	0	0	0	0
5/29/07	27.1	8.57	13.91	0	0	0	0	0	0
5/30/07	27.2	9.53	11.96	0	0	0	0	0	0

Appendix A Table 5. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species for samples taken near Lillington, NC (rkm 273) on the Cape Fear River in 2007.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/9/07	10.7	9.75	61.44	0	0	0	0	0	0
3/12/07	11.7	9.8	98.69	0	0	0	0	0	0
3/15/07	15	8.41	20.24	0	0	0	0	0	0
3/19/07	10.2	8.85	61.30	0	0	0	0	0	0
3/22/07	12.8	8.6	90.03	0	0	0	0	0	0
3/26/07	14.7	7.54	77.50	0	0	0	0	0	0
3/29/07	18.1	7.77	54.90	0	0	0	0	0	0
4/2/07	18	8.02	72.56	0	0	0	0	3	5
4/5/07	19.5	7.74	43.84	0	0	0	0	0	0
4/9/07	15	9.85	36.04	0	0	0	0	0	0
4/12/07	17.3	9.54	53.11	0	0	0	0	0	0
4/20/07	14.6	9.59	194.66	0	0	0	0	0	0
4/23/07	15.9	9.2	108.63	0	0	0	0	0	0
4/25/07	17.9	8.14	165.06	0	0	0	0	0	0
5/2/07	23.7	7.5	31.79	0	0	0	0	0	0
5/3/07	24.4	7.62	65.18	0	0	0	0	0	0
5/8/07	19.8	8.72	61.82	0	0	0	0	0	0
5/10/07	25.1	8.78	76.53	0	0	0	0	0	0
5/14/07	22.8	7.55	58.14	0	0	0	0	0	0
5/15/07	24	7.73	62.18	0	0	0	0	0	0
5/22/07	24.7	8.15	56.44	0	0	0	0	0	0
5/23/07	27.4	8.92	27.28	0	0	0	0	0	0
5/29/07	28	7.1	65.24	0	0	0	0	0	0
5/30/07	27.8	6.95	56.45	0	0	0	0	0	0

Appendix A Table 6. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species in samples taken at Lock and Dam 1 (rkm 97) on the Cape Fear River in 2008.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/5/08	13.2	11.57	87.13	0	0	0	0	0	0
3/10/08	13.3	9.78	131.96	0	0	0	0	0	0
3/13/08	12.7	11.17	95.63	0	0	0	0	0	0
3/18/08	14.2	10.92	88.36	0	0	0	0	0	0
3/20/08	14.5	9.64	101.80	0	0	0	0	0	0
3/24/08	14.9	9.19	73.87	0	0	0	0	0	0
3/25/08	14.3	9.47	36.27	0	0	0	0	0	0
3/27/08	14.8	9.10	64.22	0	0	0	0	0	0
4/1/08	15.5	9.38	68.50	0	0	0	0	0	0
4/3/08	15.8	9.05	110.00	0	0	0	0	0	0
4/7/08	15.9	7.12	125.02	0	0	0	0	0	1
4/9/08	15.4	8.09	132.25	0	0	0	0	0	0
4/15/08	18.0	8.88	97.01	4	0	0	0	0	0
4/17/08	17.1	9.27	95.06	0	0	0	0	0	0
4/21/08	17.9	9.59	76.39	1	0	0	0	0	0
4/23/08	18.7	9.33	90.98	4	0	0	0	0	0
4/30/08	20.5	8.29	31.91	159	0	0	1	0	0
5/1/08	20.6	8.00	105.89	0	0	6	1	0	3
5/7/08	21.2	7.26	43.81	0	0	0	0	2	2
5/8/08	21.6	7.06	36.67	9	0	0	0	1	0
5/12/08	22.4	6.52	30.63	5	0	0	0	0	0
5/12/08	22.3	6.58	39.20	9	0	0	0	0	1
5/12/08	22.3	6.54	33.75	0	0	0	0	0	1
5/12/08	22.3	6.56	36.74	0	0	0	0	0	0
5/15/08	22.1	7.71	75.16	90	0	1	1	4	0
5/19/08	22.1	8.10	73.27	80	0	0	0	3	2
5/19/08	22.0	8.11	74.92	53	0	0	0	1	0
5/19/08	21.9	8.09	81.02	17	0	0	0	0	0
5/19/08	21.9	8.00	68.60	1	0	0	0	0	0
5/23/08	22.6	7.73	50.52	0	0	0	0	0	0
5/27/08	23.8	7.80	34.25	139	3	0	0	0	1
5/29/08	24.0	7.25	28.10	29	3	0	0	0	0
6/4/08	26.1	7.08	13.75	0	0	0	0	0	0

Appendix A Table 7. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species in samples taken at Lock and Dam 2 (rkm 149) on the Cape Fear River in 2008.

Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/6/08	13.6	10.92	80.49	0	0	0	0	0	0
3/10/08	12.1	9.91	79.23	0	0	0	0	0	0
3/11/08	12.1	10.76	50.69	0	0	0	0	0	0
3/17/08	14.0	10.76	67.14	1	0	0	0	0	0
3/19/08	14.1	10.53	61.90	0	0	0	0	0	0
3/27/08	14.8	9.63	39.49	0	0	0	0	0	0
4/1/08	15.9	8.94	48.00	2	0	0	0	0	0
4/2/08	15.0	8.97	49.03	0	0	0	0	0	0
4/8/08	15.0	7.25	94.03	4	0	0	0	0	0
4/9/08	15.3	8.33	53.53	1	0	0	0	0	0
4/15/08	17.2	8.46	59.84	1	0	0	0	1	0
4/17/08	16.0	9.36	57.80	4	0	0	0	0	0
4/21/08	18.3	8.97	62.81	13	0	0	0	3	0
4/23/08	18.2	8.89	66.42	9	0	0	0	0	0
4/30/08	20.4	7.50	30.79	13	0	0	0	2	0
5/1/08	19.4	7.25	22.76	0	0	3	0	13	2
5/6/08	21.0	7.23	34.90	0	0	0	0	3	0
5/7/08	21.7	6.80	30.36	0	0	0	0	3	0
5/13/08	21.9	7.25	40.06	7	0	0	0	1	0
5/14/08	21.7	7.36	57.90	0	0	1	0	0	1
5/21/08	22.3	7.76	54.25	2	0	0	0	0	0
5/22/08	22.6	7.74	41.04	0	0	0	0	0	0
5/26/08	22.8	7.30	33.79	0	0	0	0	0	0
5/27/08	23.4	7.15	31.97	0	0	0	0	0	0

Appendix A Table 8. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species in samples taken at Lock and Dam 3 (rkm 186) on the Cape Fear River in 2008.

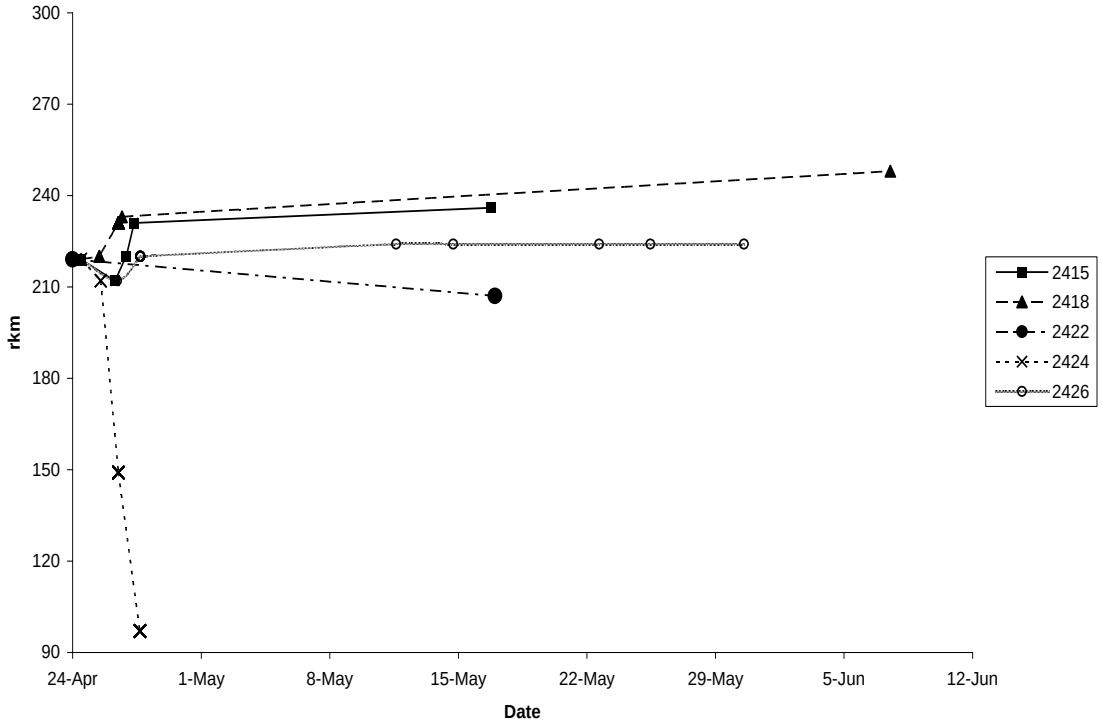
Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/11/08	11.8	11.27	62.50	0	0	0	0	0	0
3/12/08	12.6	11.28	82.64	0	0	0	0	0	0
3/17/08	13.7	10.75	88.65	0	0	0	0	0	0
3/19/08	13.7	10.97	68.79	0	0	0	0	0	0
3/25/08	14.2	9.70	54.63	0	0	0	0	0	0
3/26/08	13.9	10.47	62.54	0	0	0	0	0	0
3/31/08	14.6	8.95	71.42	0	0	0	0	0	0
4/2/08	15.6	9.17	80.82	0	0	0	0	0	0
4/8/08	15.0	8.18	99.14	0	0	0	0	0	0
4/10/08	16.2	8.03	94.96	0	0	0	0	0	0
4/14/08	17.3	6.73	68.08	13	0	0	0	0	0
4/16/08	15.7	9.60	86.23	0	0	0	0	0	0
4/22/08	17.9	9.00	73.78	4	0	0	0	0	1
4/30/08	19.8	7.77	76.31	5	0	4	0	2	2
5/1/08	18.9	7.82	82.84	2	0	6	0	0	8
5/6/08	21.2	7.68	61.80	0	0	0	0	0	1
5/8/08	22.0	7.55	49.71	0	0	19	1	0	2
5/13/08	21.0	7.33	57.61	5	0	0	0	0	2
5/14/08	20.6	7.81	101.09	0	0	0	0	0	0
5/20/08	22.1	7.98	34.71	0	0	0	0	0	0
5/21/08	22.2	7.60	58.40	0	0	0	0	0	0
5/26/08	22.9	7.77	49.07	0	0	0	0	0	0
5/28/08	23.0	7.39	41.39	4	0	0	0	0	3

Appendix A Table 9. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species for samples taken in Fayetteville, NC (rkm 226) on the Cape Fear River in 2008.

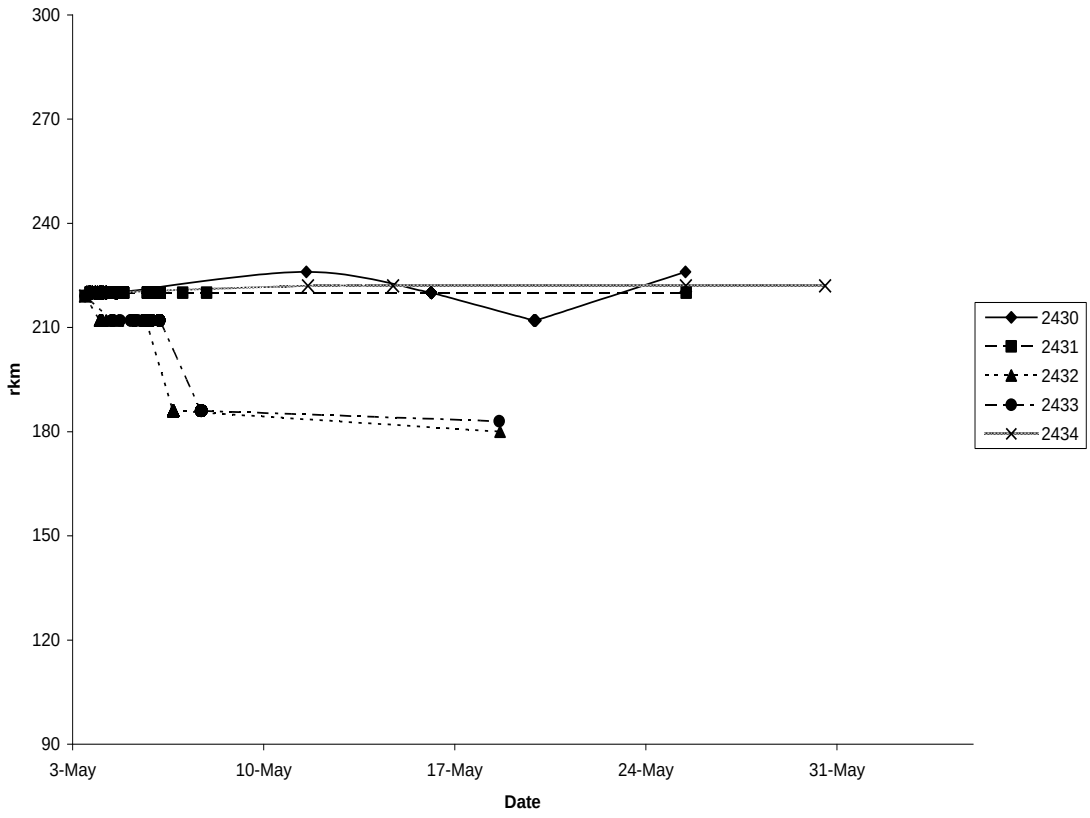
Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/6/08	13.5	10.15	117.16	0	0	0	0	0	0
3/11/08	11.5	11.27	55.25	0	0	0	0	0	0
3/13/08	13.0	11.47	83.88	0	0	0	0	0	0
3/17/08	13.4	11.10	83.98	0	0	0	0	0	0
3/19/08	13.2	11.03	85.98	0	0	0	0	0	0
3/24/08	14.2	9.19	67.02	0	0	0	0	0	0
3/26/08	14.2	11.15	61.49	0	0	0	0	0	0
3/31/08	13.3	9.37	56.94	0	0	0	0	0	0
4/2/08	15.6	8.66	70.60	0	0	0	0	0	0
4/8/08	14.5	8.52	116.63	0	0	0	0	0	0
4/10/08	16.7	7.92	61.65	0	0	0	0	0	0
4/14/08	16.7	6.83	85.55	0	0	0	0	0	0
4/16/08	16.2	9.60	60.24	0	0	0	0	0	0
4/22/08	16.9	9.29	75.37	2	0	0	0	0	0
4/30/08	19.0	8.38	100.12	0	0	0	1	5	4
5/1/08	18.5	7.97	82.70	1	0	0	0	1	3
5/6/08	22.7	7.05	43.04	0	0	0	0	0	0
5/8/08	21.6	7.09	37.95	0	0	0	0	0	0
5/13/08	21.1	7.85	51.45	1	0	0	0	0	0
5/15/08	20.5	8.24	78.49	0	0	0	0	0	1
5/20/08	22.3	7.80	72.95	0	0	1	0	2	0
5/21/08	22.3	7.50	46.82	0	0	0	0	0	0
5/27/08	24.3	6.93	31.72	0	0	0	0	0	0
5/29/08	22.8	6.26	26.84	0	0	0	0	0	0

Appendix A Table 10. Water Temperature, Dissolved oxygen, volume of water filtered, and number of eggs collected of each species for samples taken in Lillington, NC (rkm 276) on the Cape Fear River in 2008.

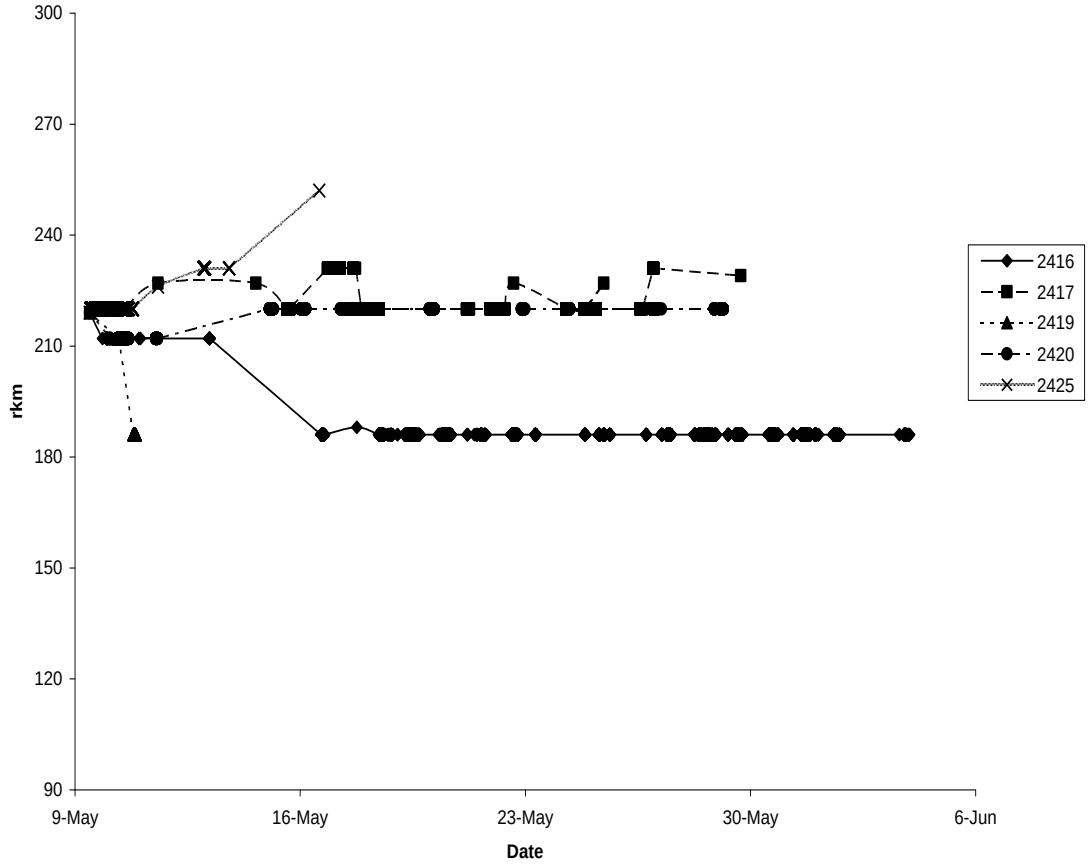
Date	Water Temp. (C°)	D.O. (Mg/L)	Volume Sampled (m3)	American Shad Eggs	American Shad Larvae	Striped Bass Eggs	Striped Bass Larvae	Non-target Eggs	Non-target Larvae
3/6/08	14.0	10.80	41.24	0	0	0	0	1	0
3/11/08	11.8	11.57	59.42	0	0	0	0	0	0
3/13/08	11.1	11.76	61.41	0	0	0	0	0	0
3/17/08	13.7	11.56	103.92	0	0	0	0	0	0
3/19/08	13.7	11.25	57.45	0	0	0	0	0	0
3/24/08	13.7	9.81	48.18	0	0	0	0	0	0
3/26/08	14.6	10.02	35.49	0	0	0	0	0	0
3/31/08	14.3	9.31	44.21	0	0	0	0	0	0
4/2/08	15.5	9.03	25.74	0	0	0	0	0	0
4/8/08	14.9	9.05	84.85	0	0	0	0	0	0
4/10/08	17.0	8.42	79.62	0	0	0	0	0	0
4/14/08	15.6	6.94	64.46	0	0	0	0	0	0
4/16/08	17.1	10.35	67.12	0	0	0	0	0	0
4/22/08	18.3	9.73	72.61	0	0	0	0	0	0
4/25/08	18.4	8.40	49.86	0	0	0	0	0	0
4/30/08	18.6	8.68	82.41	0	0	0	0	2	9
5/1/08	19.3	8.00	56.68	0	0	0	0	0	6
5/6/08	22.1	7.80	17.21	0	0	0	0	0	0
5/8/08	22.9	7.29	15.15	0	0	0	0	0	0
5/13/08	20.6	8.00	46.51	0	0	0	0	0	1
5/15/08	20.3	8.94	52.30	0	0	0	0	0	0
5/20/08	22.1	8.07	61.86	0	0	0	0	0	0
5/21/08	21.7	7.55	41.35	0	0	0	0	0	0
5/27/08	25.6	7.29	13.34	0	0	0	0	0	0
5/29/08	22.1	6.33	15.45	0	0	0	0	2	0



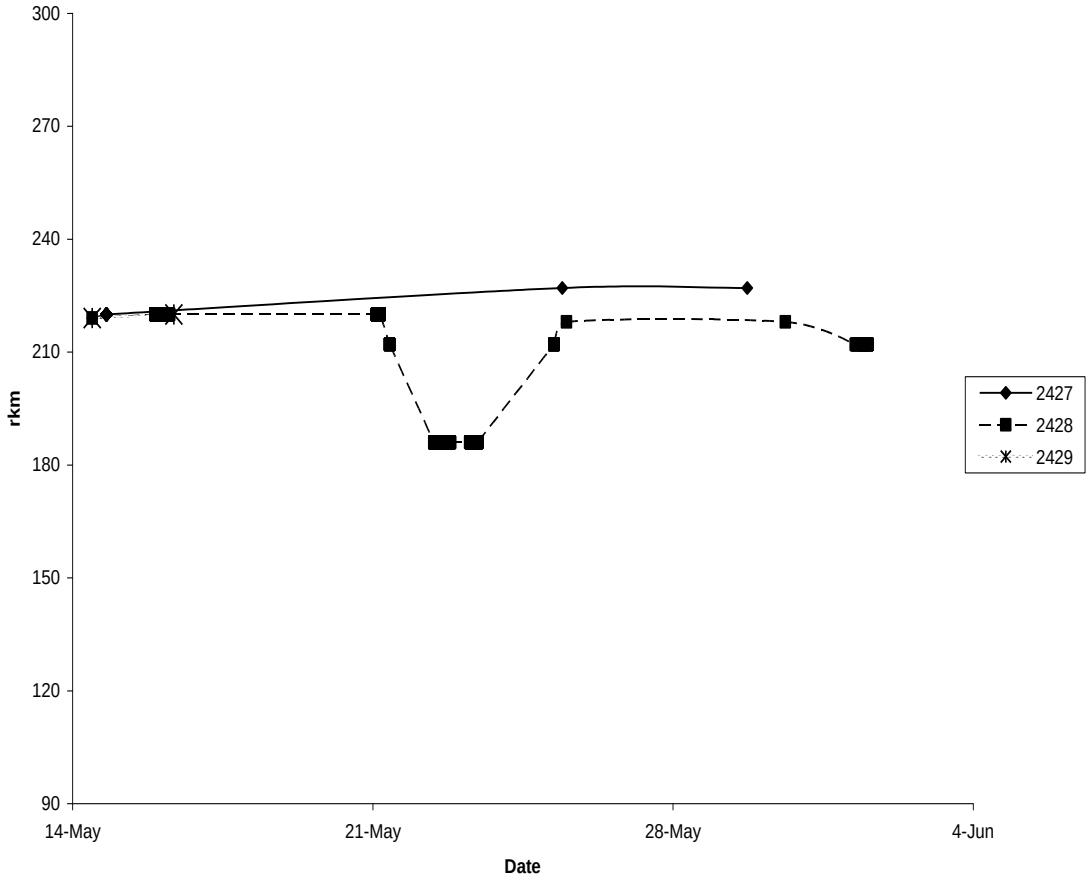
Appendix B Figure 1. Movement of tagged American shad, released on April 24, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



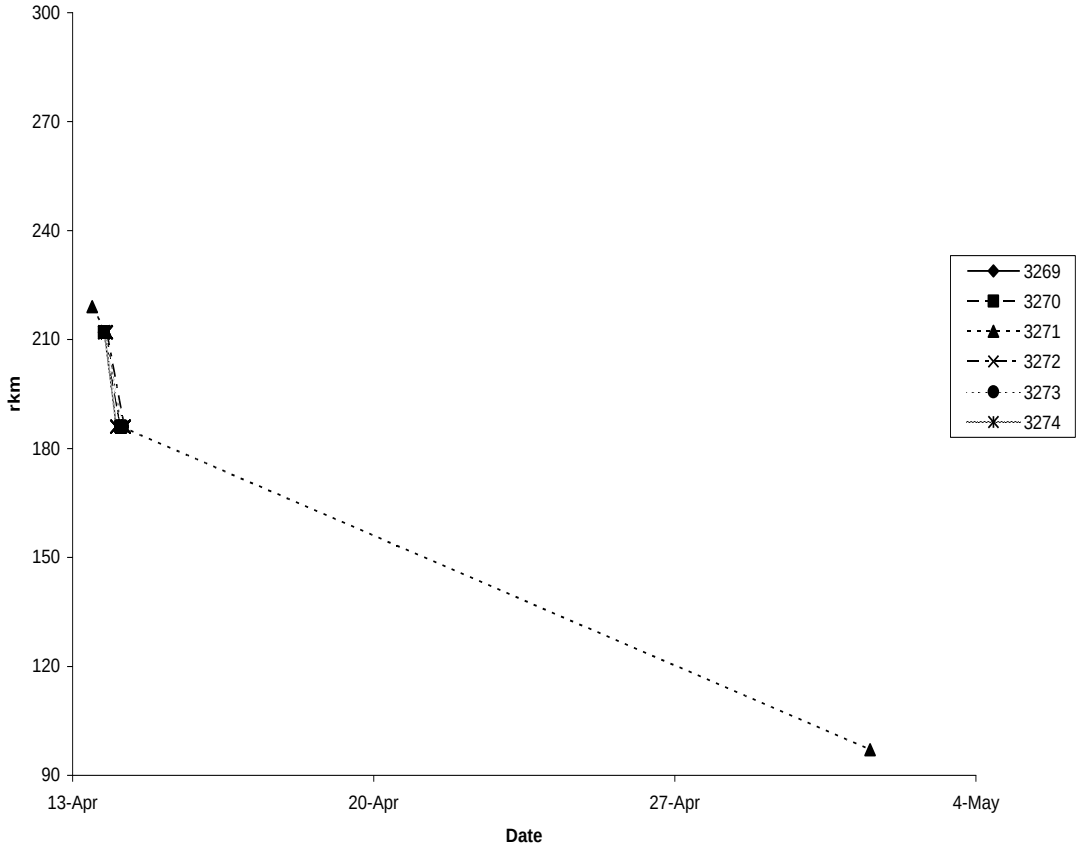
Appendix B Figure 2. Movement of tagged American shad, released on May 3, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



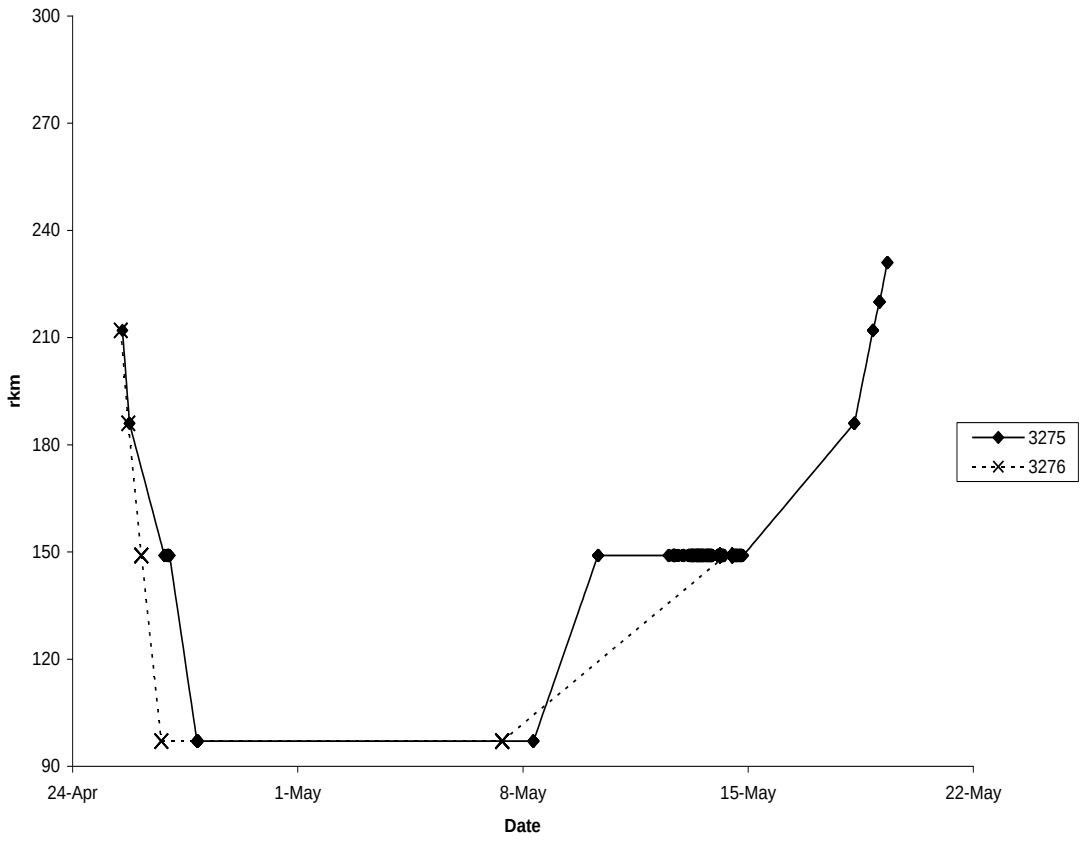
Appendix B Figure 3. Movement of tagged American shad, released on May 9, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



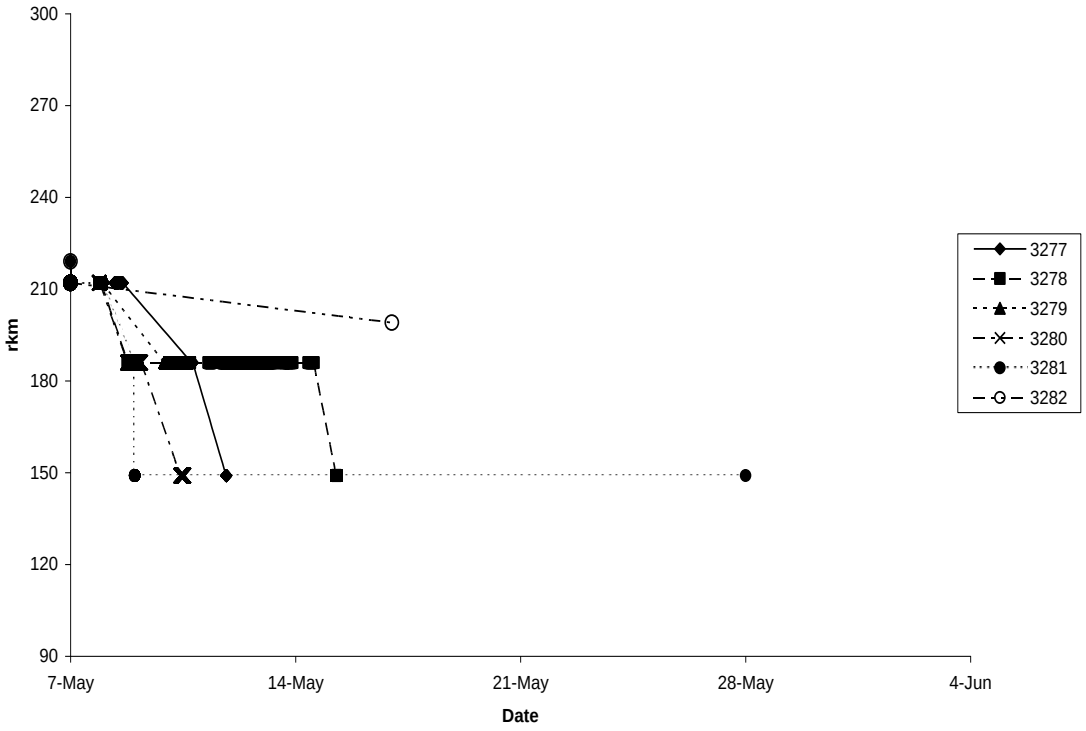
Appendix B Figure 4. Movement of tagged American shad, released on May 14, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking . Legend numbers correspond to tag numbers of individual fish.



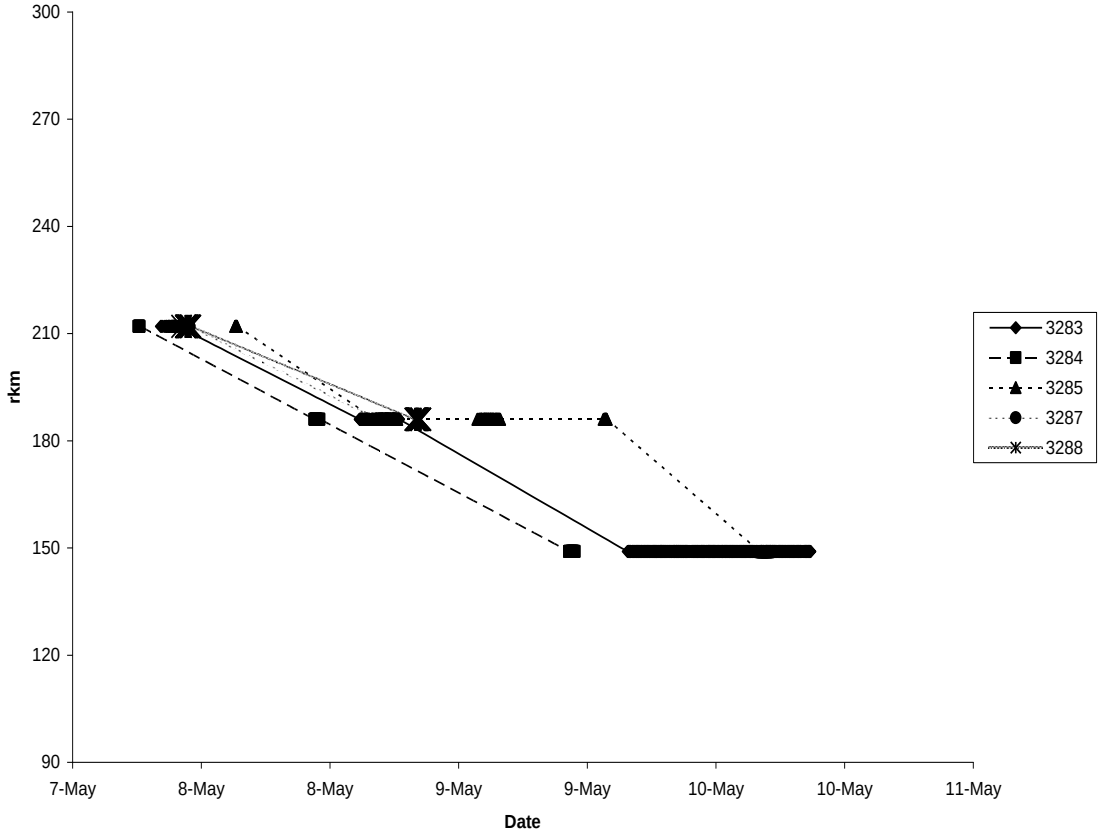
Appendix B Figure 5. Movement of tagged striped bass, released on April 13, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking . Legend numbers correspond to tag numbers of individual fish.



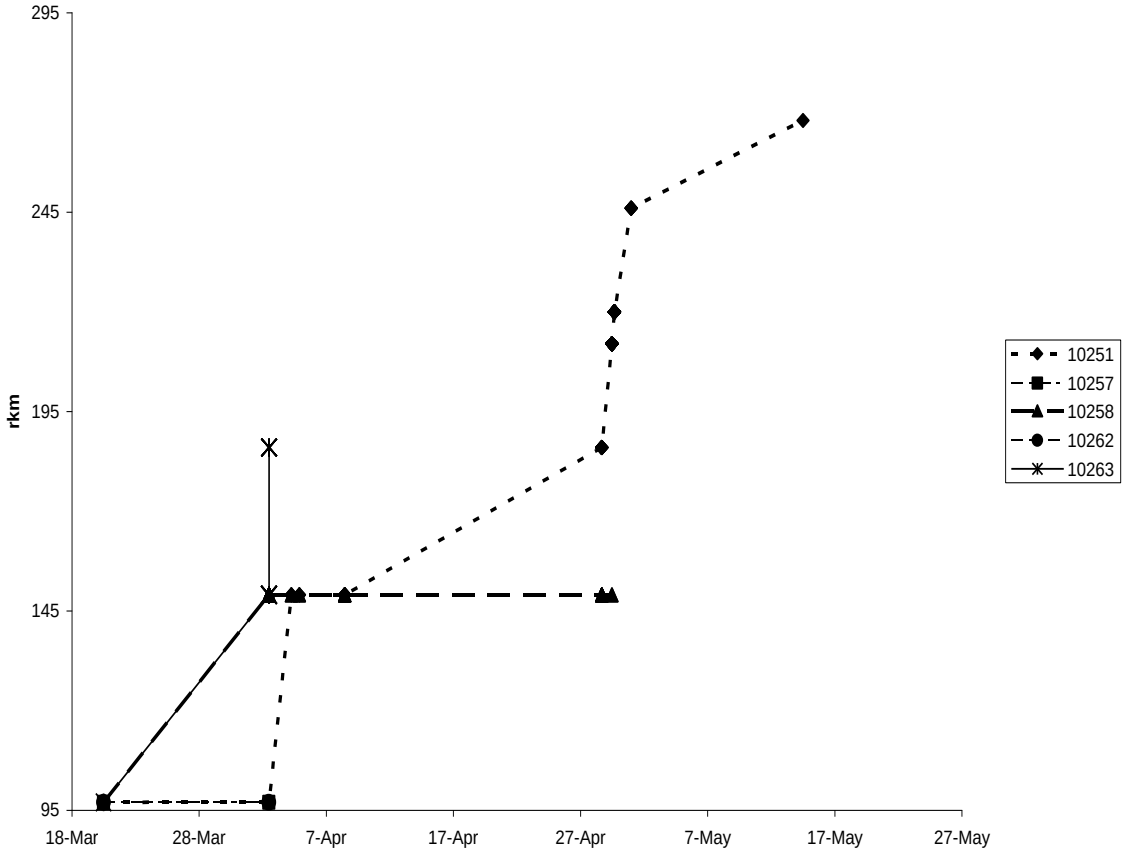
Appendix B Figure 6. Movement of tagged striped bass, released on April 24, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



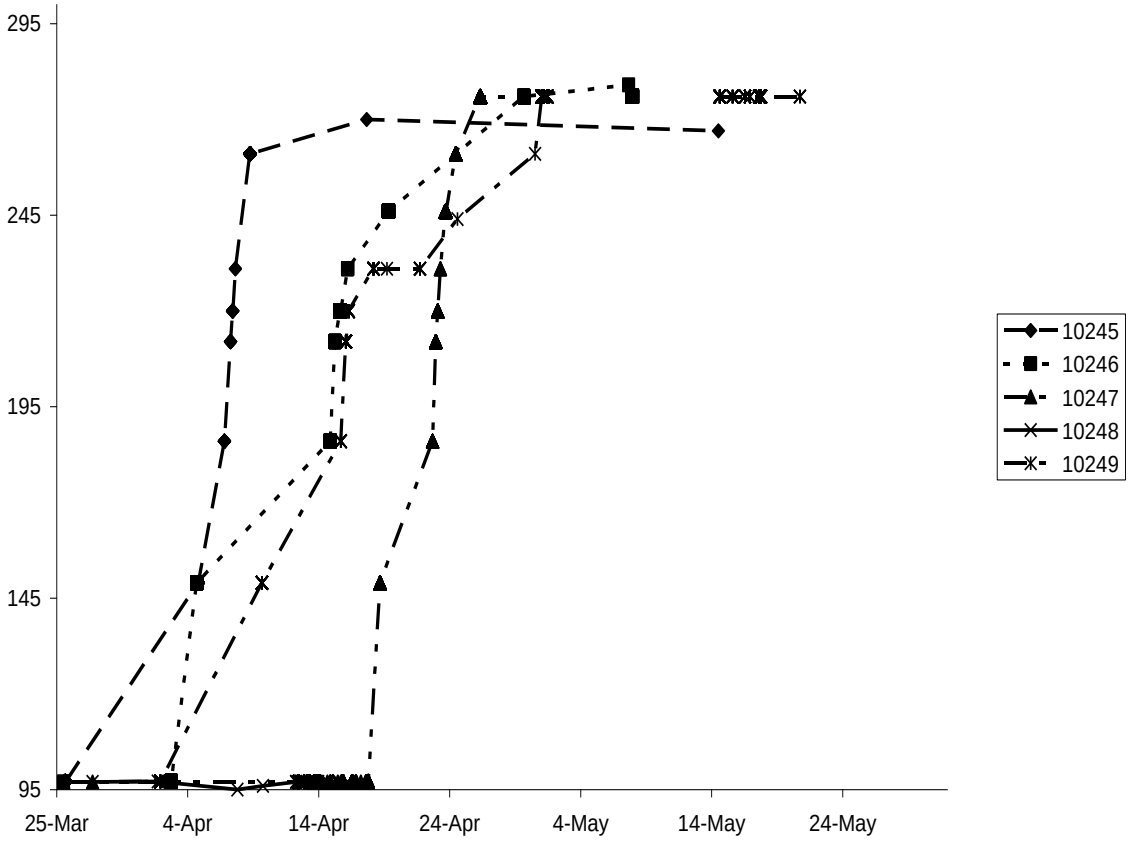
Appendix B Figure 7. Movement of tagged striped bass, released on May 7, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



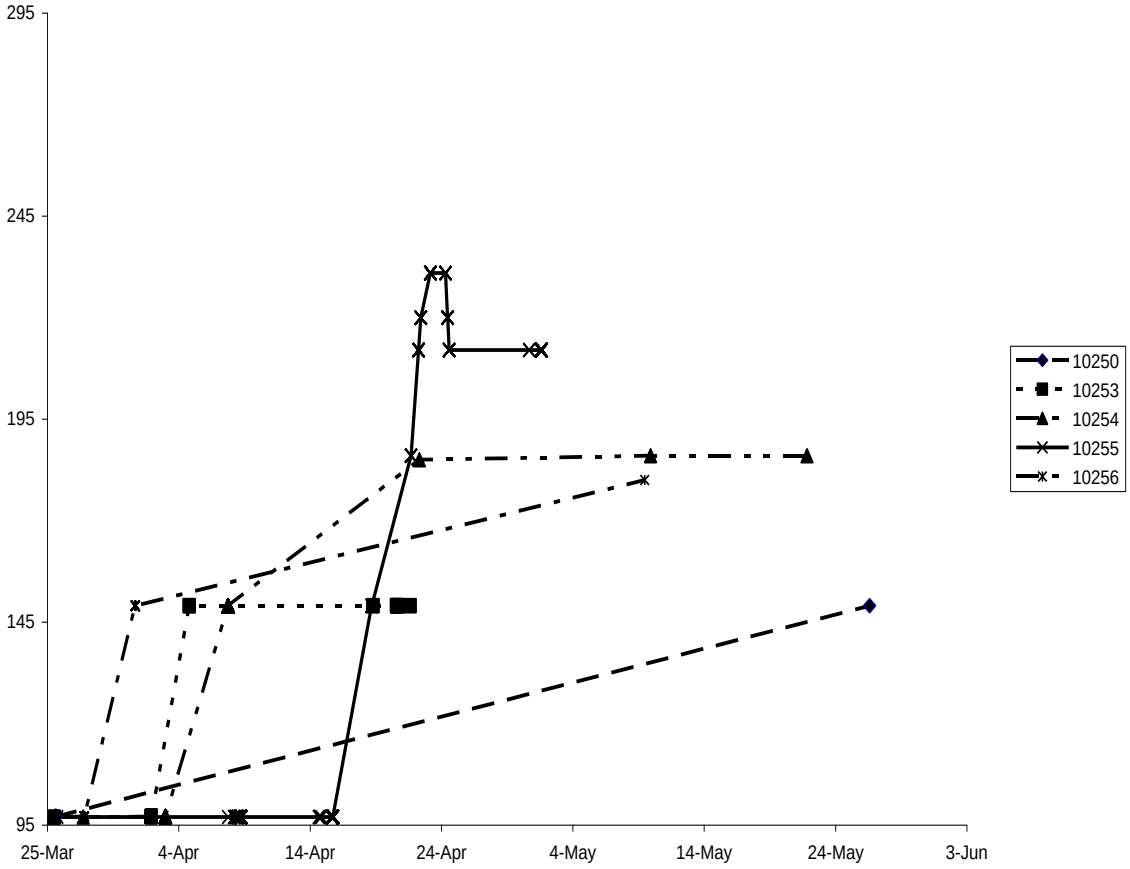
Appendix B Figure 8. Movement of tagged striped bass, released on May 7, 2007 at river km 219 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



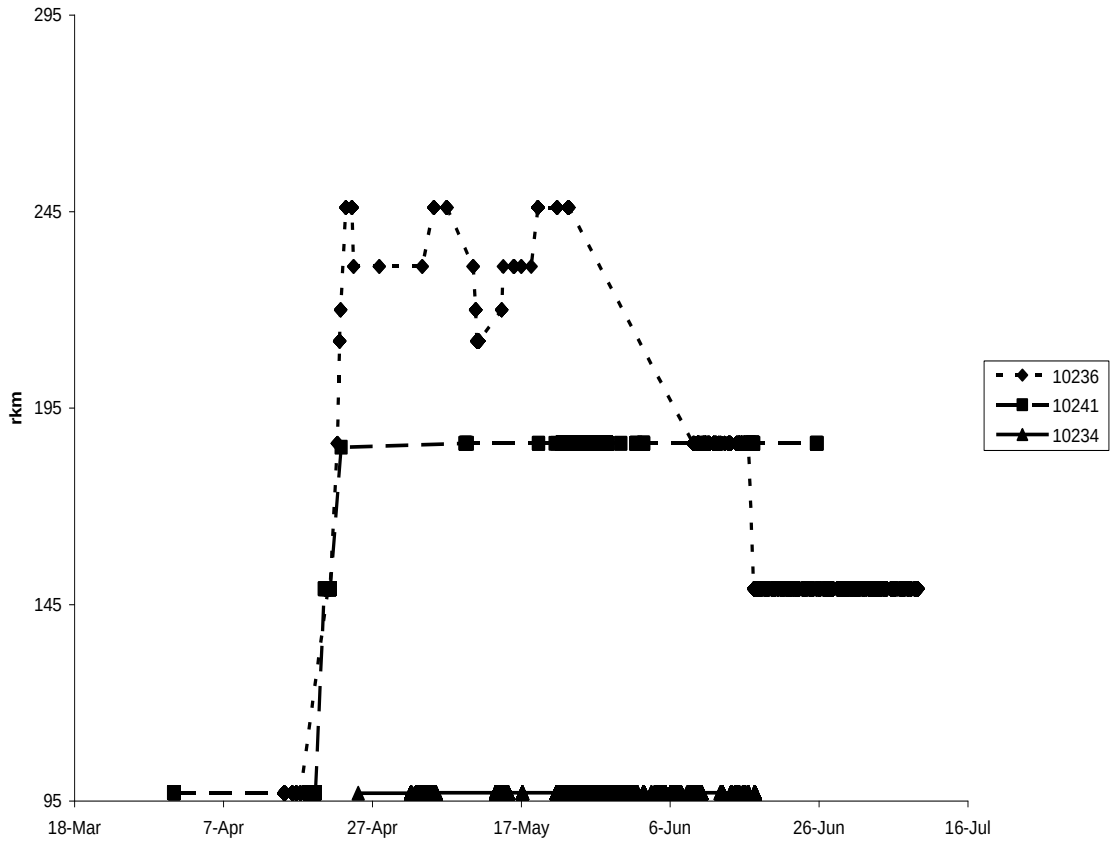
Appendix C Figure 1. Movement of tagged American shad, released on March 18 and 20 (fish 10251), 2008 below lock and dam 1 (rkm97) in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



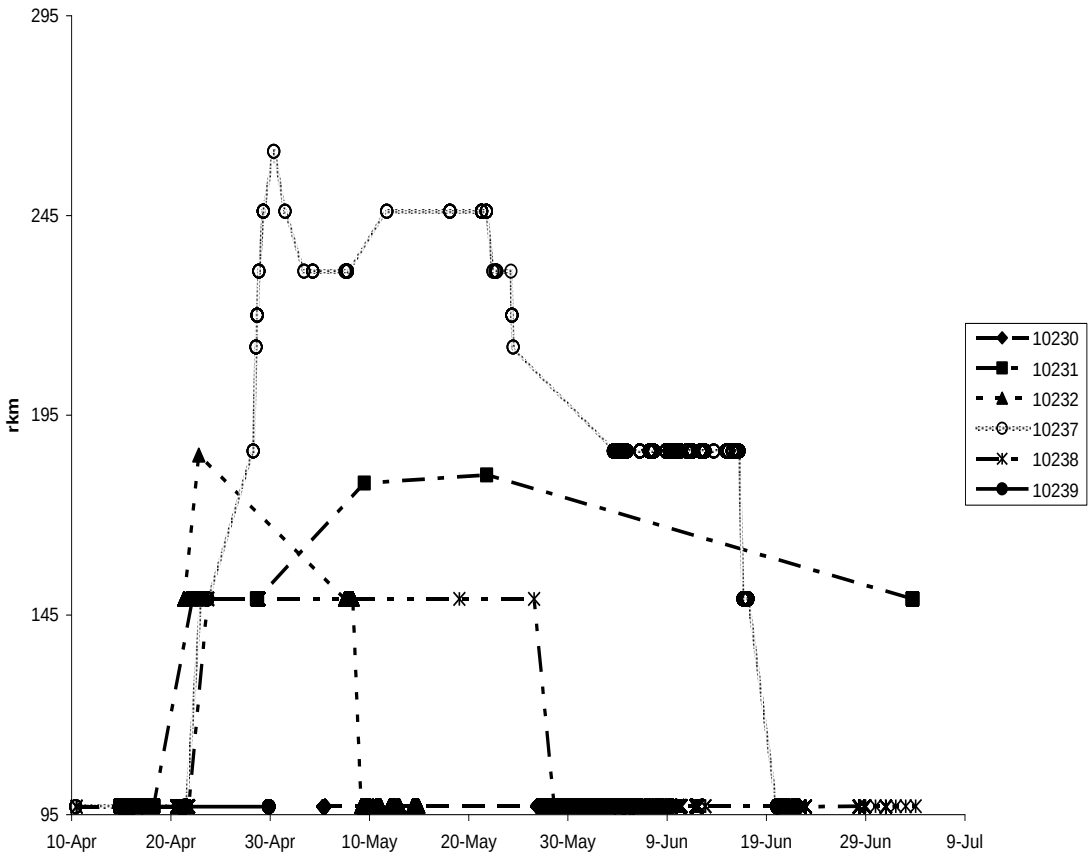
Appendix C Figure 2. Movement of tagged American shad, caught and released inside the lock chamber at lock and dam 1 (rkm97) on March 25, 2008 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



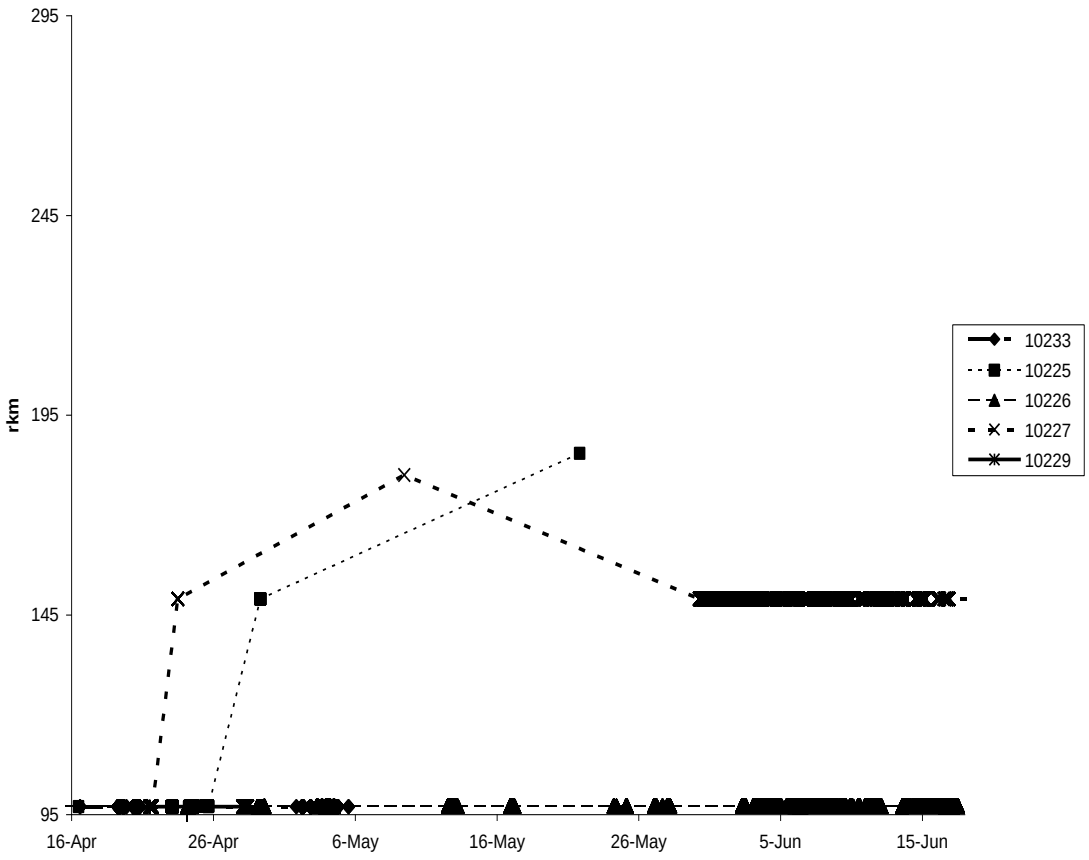
Appendix C Figure 3. Movement of tagged American shad, caught and released inside the lock chamber at lock and dam 1 (rkm97) on March 25, 2008 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



Appendix C Figure 4. Movement of tagged striped bass, caught and released below lock and dam 1 (rkm97) in the Cape Fear River, NC. Fish 10241 was released on March 28, 2008, fish 10236 on March 27, 2008, and fish 10234 on April 15, 2008. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



Appendix C Figure 5. Movement of tagged striped bass, caught and released below lock and dam 1 (rkm97) on April 15, 2008 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.



Appendix C Figure 6. Movement of tagged striped bass, caught and released below lock and dam 1 (rkm97) on April 16 (fish 10233 & 10225) and 21 (fish 10226-9), 2008 in the Cape Fear River, NC. Locations are based on results of both stationary receivers and manual tracking. Legend numbers correspond to tag numbers of individual fish.