

ABSTRACT

MITCHELL, WARREN ANDERSON. Estimating run size of anadromous fishes in the Roanoke River, North Carolina, using hydroacoustics. (Under the Direction of Joseph E. Hightower.)

The annual arrival of American shad *Alosa sapidissima*, striped bass *Morone saxatilis* and hickory shad *Alosa mediocris* is ecologically and economically important in the rivers of North Carolina. Both species support commercial and recreational fisheries, and both are the focus of management efforts by state and federal agencies. Reliable information about population levels is essential for effective management. The goal of this study was to estimate the number of adult spawners returning to the Roanoke River. During April-May 2004 and March-May 2005, a stationary 430 kHz hydroacoustic system was deployed on the river bottom in a side-aspect orientation. Tracks of upstream-migrating fish were discernable from ambient noise. The number of fish migrating upstream was slightly lower during 00:00-08:00 compared to the other two 8-hr periods of the day. A majority of fish tracks were within 2 m of the river bottom in both years (89%), and were more associated with ranges near shore. Drift gill netting and boat electrofishing appear to provide an adequate measure of the seasonal presence and absence of target species, though electrofishing provides better samples size. These traditional fisheries methods confirmed the expected seasonal pulses of hickory shad, followed by striped bass, during both years. Counts of upstream fish tracks were low during periods between these pulses. Daytime electrofishing catch rates for 2005 were correlated with daily counts of upstream fish tracks. American shad occurred sporadically at low abundance throughout both years. It was the main target species in this study but made up less than 2% of the catch in both years. A majority of fish captured by gill netting (85%) were within two meters of the river bottom. Analysis methods

were standardized in 2005 based on lessons learned in 2004. The 2004 species-specific estimates were 9,046 American shad and 126,176 striped bass. The default estimates (and SEs) for 2005, assuming a uniform cross-channel density of upstream migrants, were 7,054 (450) American shad and 118,778 (4,799) striped bass. Using alternative assumptions about detectability of fish tracks and the cross-channel distribution of upstream migrants, estimates ranged between 5,422 (346) and 13,604 (887) American shad and 94,529 (3,807) and 534,750 striped bass. This first large-scale assessment of the Roanoke River American shad population is difficult to compare with surveys of relative abundance. Estimates of striped bass abundance appear low when compared to traditional stock assessment results. The largest uncertainties regarding the hydroacoustic monitoring is the cross-channel distribution of upstream migrants. For American shad, our study points to the difficulty in assessing the abundance of a target species that is rare in biological samples. Using hydroacoustics to estimate run sizes appears to be feasible, but improvements to the study design are needed. Further validation will improve both accuracy and precision of estimates, and allow fishery managers to use hydroacoustic results with confidence in making management decisions.

**ESTIMATING RUN SIZE OF ANADROMOUS FISHES IN THE ROANOKE RIVER,
NORTH CAROLINA, USING HYDROACOUSTICS**

by
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BIOGRAPHY

I was born in Palm Beach Gardens, Florida to loving parents, and shared my childhood with a first-rate brother. I split my youth between central Kentucky and south Florida, and rounded a Southeastern U.S. upbringing with trips to my Aunt's farm in the Clinch Mountains of Tennessee and time at my Grandmother's cottage in Fulton County, Texas. Upon returning to south Florida at age 14, recreational offers from my peers of, "Let's meet at the mall and see a movie," expanded to include, "The tide is incoming on Saturday morning, want to drift the river and spear fish?" My curiosity in biological communities and the scientific method was awakened in the wet environment of the Loxahatchee River. By the time I was faced with career decisions, my outdoor experiences were distilled to an inclusive interest in observing natural environments.

I graduated from Jupiter High School in 1993, and enrolled at the Florida Institute of Technology in Melbourne. This satisfied a youthful attraction to marine science and collegiate soccer, and the experience was sublime. I earned a BS in Biological Oceanography in 1997, and harvested valuable lessons in leadership, self-reliance and perseverance from my varsity sport experience. Upon graduation – my professional aspirations blithely outlined – I set out for diverse and tangible adventures. During my twenties I took term employment with federal, state, private and non-profit organizations, each addressing science and professional development in a different manner. Field observations took me from salmon streams in southeast Alaska to marine canyons in the Gulf of Mexico. I took children snorkeling on the coral reefs of the Florida Keys, and swapped wheelhouse stories with swordfish boat skippers on the Grand Banks. Owing to my

experiences and oceanography training, I gained an affinity for macro-scale study, and in particular how humans affect fish population dynamics.

My interests and enthusiasm came together one fall day in 2003 when Dr. Joe Hightower advertised a graduate student position. Both hydroacoustic technology and the story of anadromous populations in the Southeast U.S. attracted my interest. It was with great personal pleasure and gratitude that I accepted my position here at North Carolina State University.

Months later on the Roanoke River, drifting nets under a full moon to the soundtrack of barred owls, I considered myself luckier than I had right to be. I've cultivated a deep appreciation for this beautiful state, and that includes the native population who kept me so sustained by technical support, laughs and Sunday dinners while in the field. I am anxious to continue my development as a scientist and an individual, and I pause now to recognize those who have assisted me thus far.

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Two spring seasons of field research would not have been possible without the dedicated service of two technicians. Gery Cox worked for the project in 2004, and his dedication to task, persistent optimism and technical assistance are genuinely appreciated. Steve Meyer assisted in 2005; his skills in sampling and handling fish, flexibility while at task, and good humor were especially helpful.

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During two field seasons it was my pleasure to do business with Bill Johnson, well known as “The Rambling Ex-Ranger of the Roanoke.” In addition to his support for the research, I am grateful for the time I spent with such a seasoned and savvy octogenarian. Residents of the Sycamore Shores community were also especially generous and welcoming: the Bearden, Callahan, Lee, Levey, Peacock and Sieber families; Cole and Keith.

My immediate family have always provided kind and enthusiastic support, and continued to do throughout my time at NCSU: Hazen, John and Marthanne Mitchell. Lastly, I am very thankful for the support of my wife, Jenny Vander Pluym. Her comforting love is treasured, and after seven years of pursuit and two years of marriage I value every day we have together more than the last.

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INTRODUCTION

Anadromous species of fish spend the majority of their adult lives in the ocean, and make yearly migrations (runs) inland to spawn (Myers 1949, cited in McDowall 1997). These migrations between distant habitats are assumed to provide benefits to long-term survival and reproduction that outweigh the risks and energetic costs of migration (Gross 1987). However, a disadvantage of this life history strategy is that concentration of many individuals in a relatively small amount of habitat can greatly increase a population's vulnerability to harvest and other sources of mortality. For example, Yarrow (1874) documented dramatic declines in spawning runs of American shad *Alosa sapidissima* due to intensive fishing within coastal rivers. For some species, harvest in coastal rivers still comprises a substantial fraction of total annual mortality (e.g., Dorazio 1995). Reliance on freshwater spawning habitat also exposes migratory populations to anthropogenic effects on river flow, habitat and water quality (Trent and Hassler 1968, Legget and Whitney 1972, Rulifson 1994, Lucas and Baras 2001).

Anadromous species are economically and ecologically important to coastal river systems. They historically supported commercial fisheries that provided many jobs to coastal areas (McDonald 1887). More recently, species such as American shad and striped bass *Morone saxatilis* support a combination of commercial and recreational fishing, including considerable catch-and-release fishing (NCWRC and NCDMF 2004). From an ecological perspective, juvenile *Alosa* are important estuarine prey species and migrating adults import marine-derived nutrients to freshwater systems (Walburg and Nichols 1967, Garman 1992, Garman and Macko 1998, Limburg et al. 2003, Wipfli et al. 2003).

American shad are known to enter their natal streams after water temperature reaches

4°C, and initiate spawning between 14-21°C (Walburg and Nichols 1967, Leggett and Whitney 1972). Striped bass in the Roanoke River typically begin spawning when water temperatures reach 18°C, with the most intense spawning between 20-23.9°C (Rulifson 1990). Bilkovic et al. (2002) found that spawning activity for the two species overlapped temporally, and to a lesser degree spatially, in two coastal rivers in Virginia. The annual migration period in North Carolina is expected for both species between March and June.

This study focuses on a novel method to estimate the true run size for two anadromous species in the Roanoke River, North Carolina: American shad and striped bass. American shad migrations have been of keen commercial interest to residents of North Carolina since before the American Revolutionary War. Public concern for conservation was documented in the early 20th century following a peak in historical landings (Stevenson 1899, Hightower et al. 1996). As a result of overfishing, habitat change and dam construction, American shad in the Roanoke River are currently considered to be at a low population level (Rulifson 1994, Hightower et al. 1996, Limburg et al. 2003), and a restoration program is underway. In addition to stocking hatchery-raised fry, the program includes a plan to reintroduce adult American shad to currently inaccessible sections of the upper Roanoke River basin, and perhaps install fish passage facilities at hydropower dams operated by Dominion / North Carolina Power (Dominion). The recent Federal Energy Regulatory Commission (FERC) license which allows Dominion to operate two hydroelectric projects requires that population size be estimated annually. Estimates of run size must be highly reliable, as they will serve as the trigger for some aspects of the restoration program (FERC 2003).

Estimates of striped bass run size are also desired for the Roanoke River, but for a

very different reason. The successful Roanoke River recreational fishery is economically important to eastern North Carolina, and the population is thought to be at a record abundance level (NCWRC and NCDMF 2004). Harvests are intensively managed and public pressure exists to increase quotas. An estimate of run size based on hydroacoustic monitoring by Hewitt (2003) was considerably lower than estimates based on virtual population analysis. Further monitoring is warranted to assess the reliability of the hydroacoustic estimates of absolute abundance.

Management of Atlantic slope anadromous species is often based on commercial and recreational catch monitoring plus auxiliary survey data on relative abundance (e.g., NCWRC and NCDMF 2004, NCWRC 2004, SBSAS 2005). These data may be collected in estuarine waters where runs from multiple river systems are mixed. The results allow for management on a regional scale but cannot reliably be used to manage individual populations. A more desirable approach for local management is to estimate the true number of fish that return to a single river.

River-specific monitoring is commonly done for salmonids. The goal is generally to estimate escapement, or the number of spawners that have migrated upriver to spawn. These methods allow for precise management, often in real-time, but most are cost-prohibitive or inappropriate on the Roanoke River. For example, counting fences (weirs) have been constructed across entire river channels, allowing researchers to count each passing salmon at a break in the weir (Hilborn et al. 1999, Holmes et al. 2006). However, use of weirs is not feasible in deep rivers and areas where river navigation is a concern. Enumerating techniques such as visual census, aerial survey, and redd counting rely on excellent water clarity (Jones et al. 1998, Parken et al. 2003, Shardlow 2004), which is rare in Southeastern

coastal rivers.

Counts of individuals at fish passage facilities also have been used to characterize populations whose spawning grounds are located upstream of dams (e.g., Columbia River DART program 2006, VDGIF 2006). However, some portion of the spawning population may not utilize the passage facility (Moser et al. 2000, Bailey et al. 2004), such that these counts underestimate the true size of the spawning run. Restoration studies on the Susquehanna River successfully enumerate American shad at fish passage facilities in the watershed; however population estimates are generated from tag and recapture programs due to the uncertainty of passage efficiency (St. Pierre 2003).

When total counts cannot be made, traditional sampling methods such as electrofishing and gill netting can be used to estimate relative abundance (Hubert 1996, Reynolds 1996). These data are less useful for management because changes in relative abundance may simply reflect changes in survey catchability (Pine et al. 2003). Another practical concern is that rivers often experience variable seasonal flows and carry obstacles such as submerged trees and drifting debris that can make using these sampling methods difficult (personal observation). Mortality associated with large-scale gill-net surveys also causes concern for incidental take of anadromous species (Hopkins and Cech 1992).

An estimate of local run size would allow managers to more accurately monitor mortality imposed by an in-river fishery, and fine tune regional stock assessment results based on relative abundance indices. Information on run size may also establish whether a rebuilding program is warranted, or be used to assess the effectiveness of such efforts.

In the past few decades, use of fixed-location hydroacoustic technology has become more common as an assessment tool for riverine anadromous populations (Ehrenberg 1983,

Brandt 1996, Ransom et al. 1998, Enzenhofer and Cronkite 2000). By placing a monitoring system downstream of known spawning grounds, researchers can obtain non-intrusive counts of migrants as they swim upstream (Daum and Osborne 1998). Estimates based on hydroacoustic monitoring for striped bass in the Roanoke River were initiated by Hewitt (2003). His estimate (262,789 striped bass) was considerably lower than one based on analyses of catch data from the Albemarle Sound / Roanoke River fishery (> 750,000 striped bass). Hewitt (2003) concluded that hydroacoustics could be used effectively and efficiently to estimate true run size for anadromous species in the Roanoke River, but further monitoring and validation of the method was needed.

A riverine hydroacoustic system typically consists of a side-looking transducer, an echosounder, and a laptop computer (Figure 1). The transducer, which is controlled by the echosounder, produces electrical pulses of sound (pings) with consistent frequency, intensity, and pulse duration. Pings propagate out from a transducer as sound energy and create a conical volume of insonified water. Echoes return to the transducer, are processed by the echosounder, and recorded by the computer. Advances in technology have allowed the development of split-beam transducers, which can record the position of each acoustic target in three dimensions (Ehrenberg 1983). For a fixed-aspect transducer aimed across a river, the three dimensions are distance away from the transducer (range), vertical distance from the central axis of the beam (elevation), and horizontal distance from the central axis of the beam (upstream/downstream). An individual fish passing through the beam is identified as a continuous series of echoes, and tracked from its entry into the beam to its exit out of the beam (Ehrenberg and Torkelson 1996). The additional information provided by a split-beam transducer is valuable when monitoring the spawning runs of anadromous fishes. For

example, the migratory direction of a fish (upstream vs. downstream) can be determined from the changes in horizontal position of each echo (Nealson and Gregory 2000, Ransom 2000).

One of the variables available for each returning echo is target strength. An object's target strength value is calculated from the intensity of the reflected sound. When measured accurately and precisely it can provide a relative size measure for the target (Love 1977; Lilja et al. 2004). Variability in the target strength depends on its physical size, reflective qualities and behavior (Horne 2000). Air in the swim bladder accounts for about 90% of a fish's echo but other parts of the fish's body can affect the shape of the returning echo (Love 1980; Burwen et al. 2003). Aspect angle (the angle at which sound energy strikes the fish) is likely to be the largest source of variation for fish of a given size (Thorne 1998). When measuring sound energy returned by fish targets, a TS threshold can be used to define the minimum size of targets that will be recorded. This threshold should be low enough to record all echoes from passing species of interest (shads and striped bass) but high enough to exclude noise (e.g., debris, very small fish).

While hydroacoustic sampling determines the presence and direction of migrating individuals, the identity of a fish track cannot be directly determined (Brandt 1996, Fleischman and Burwen 2003). Supplemental sampling (e.g., trawling, gill netting, fishwheel) is often used to partition the counts of upstream migrants among species (Brandt 1996, Hewitt 2003). This sampling also provides information about fish size that can be used in ground-truthing the size classes of fish detected by the hydroacoustics system (MacLennan and Menz 1996; Hartman et al. 2000, Frear 2002; Krumme 2004).

STUDY SITE

Headwaters of the Roanoke River assemble in the Blue Ridge Mountains of Virginia, and flow downstream for over 600 river kilometers (rkm, measured from the river's mouth). The drainage includes 25,071 km² of Virginia and North Carolina (Seaber et al. 1987). The Roanoke Rapids Dam (rkm 221) is a hydropower dam located on the fall line between the Piedmont and Coastal Plain physiographic regions. It is the most seaward river barrier and the current extent of anadromous migrations (Figure 2).

This study was conducted on a river stretch located 2.4 km downstream of Halifax, NC (Figure 3). The site is approximately 19 rkm downstream from the primary striped bass spawning grounds in Weldon at rkm 209 (Trent and Hassler 1968, Rulifson 1992, Carmichael et al. 1998). The primary spawning grounds for American shad are in Roanoke Rapids at rkm 217 (Hightower and Sparks 2003). Both species would be expected to pass the research site en route to the spawning grounds. The stretch of river where hydroacoustic monitoring was done lacks eddies and pools that could result in "milling" behavior. The site had acceptable bottom topography, adequate depth and access to electric power.

METHODS

To monitor spawning migrations in the Roanoke River we employed three sampling methods at a single site in 2004 and 2005. Drift gill netting and standardized boat electrofishing were used to examine species composition and run timing. Hydroacoustic sampling was done to enumerate upstream-migrating fish. All statistics in this study were controlled for Type I error at the .05 significance level.

River environment

Water temperature, river stage, flow and depth were recorded during both years. Temperature and river stage were available from the closest USGS National Water Information System gaging station (Halifax #0208062765). The closest USGS gaging station to record flow (rather than just stage height) was located at Roanoke Rapids Dam (#02080500). Water depth values in both years were measured at the study site on a subset of dates, and linearly regressed against river stage at the Halifax USGS gaging station. From that relationship, daily mean water depth at the transducer site was estimated for each day.

Bottom topography at the transducer site was surveyed on 30 March 2004 (Figure 4). The hydroacoustic gear was mounted in a downward-looking orientation, and used to measure depth on a series of transects through the study area. Position data (latitude and longitude) for each depth reading were obtained from a networked GPS unit. Using GIS (Arcview 3.2), a contour map of the study area was constructed from depth and position. The location and heading of the transducer were added to the map (Figure 5). The contour surface was used to estimate river bottom elevation at 0.25-m intervals of range from the transducer face.

Species composition sampling

During 2004, drift gill nets were systematically sampled during all portions of day and night. The 24-hour day was divided into 6 blocks of 4 hours (00:00-03:59, 04:00-07:59, 08:00-11:59, 12:00-15:59, 16:00-19:59, 20:00-23:59), and two consecutive blocks were sampled every other day during the season. This created an 8-hour sampling window, and meant that samples were obtained from all 6 temporal blocks over 6 days. Sampling began on 15 March during daylight hours, and night sets were added after gaining familiarity with the site. Sampling during all blocks was routine when acoustic data collection began on 3 April.

Gill nets were 23 m in length with a stretch mesh size of 7, 10, or 14 cm, based on the predicted sizes of target species (Witherell and Kynard 1990; personal communication: Fred Cross, FFWCC; Dave Hewitt, VIMS; Sara Winslow, NCDMF). Depending on water depth, either 2.4-, 3.7-, 4.9- or 7.3-meter deep nets were used in order to sample the entire water column. Drifts were separated by a minimum of 10 minutes to reduce disturbance. The sampling location (Figure 3) was substantially upstream of the hydroacoustic site (> 500 m), to minimize any disturbance effects. A 100-m stretch of the river bank was marked with flagging and night-visible reflectors, and nets were drifted consistently through the same marked stretch. Each mesh size was deployed twice during a sampling effort, and the order of the three mesh sizes fished was alternated systematically (e.g., day d : 10 cm, 14 cm, 7 cm, 10 cm, 14 cm, 7 cm; day $d+1$: 7cm, 10 cm, 14 cm, 7cm, 10 cm, 14 cm). Captured fish were identified, measured to maximum total length and released. Sex was determined for migrant species when possible.

Gill net sampling was used to examine the presence, size range and daily migration patterns of anadromous species. It was hypothesized that gill netting would document the transition from an early spring, dominant pulse of hickory shad *Alosa mediocris* to a later pulse primarily of striped bass. American shad were not expected to be the most abundant species captured at any time. Fish lengths were compiled in frequency distributions to examine size classes available to hydroacoustic monitoring. Diel variation in the number of migrating fish captured by gillnetting was investigated by comparing the mean number captured within 4-hr periods, using a Kruskal-Wallis test (Zar 1999).

During 2005 drift gill netting was restricted to a single block of daytime hours, five days per week (weekdays) between 4 March and 4 June. Sampling generally took place between 08:00 and 12:00. The protocol was identical to that used in 2004 except that the distance drifted was doubled from 100 m to 200 m in response to poor catches in 2004 (see Results). In 2005 each gill net was marked in 1-m horizontal bands, and vertical position of each fish (distance from leadline) was noted when discernable.

Species composition was also estimated by electrofishing in both years. The sample site was located approximately 1000 m upstream of the gill-net site (Figure 3). Three transects were sampled with one netter in a downstream direction, once along each shoreline and down the center channel. In 2004, eight sampling efforts were made on 7 days, approximately once every two weeks between 11 March and 26 May. Both day and night samples were collected on 29 April to investigate the potential of night sampling. In 2005 sampling location and protocol were identical to the 2004 except that sampling was increased to five days per week (weekdays) and began on 4 March. Sampling generally took place between 13:00 and 17:00.

Sample periods in both years were 900 seconds for each transect, or a total of 2,700 seconds per day. Output voltage was 680 volts (pulsed DC), and pulse duration was adjusted to maintain four amps current output. Fish were identified, measured to the nearest mm and sexed when possible.

In 2004 electrofishing efforts were too few to be used in analyses, except for qualitative comparisons with drift gill netting. In 2005, electrofishing replaced gill netting as the primary gear to monitor the presence, size range and daily migration patterns of anadromous species. A Kolmogorov-Smirnov two-sample test (Zar 1999) was used to determine if the distribution of striped bass length frequencies differed significantly between primary gears in 2004 (gill netting) and 2005 (electrofishing).

In 2004 and 2005 hickory shad and striped bass dominated the catches and American shad were rare (see Results), based on the primary sampling gears. Daily catches varied considerably, however, at least in part due to small sample sizes. Smoothed proportions were calculated for hickory shad, striped bass, and American shad (the latter because of its role as target species) using 7-day moving averages. We assumed seven days was a span of time which would not over-simplify migration patterns (e.g., Acolas et al. 2006). Gill net catches in 2004 and electrofishing catches in 2005 were summed on sample day d , and averaged with sample day $d-3$, $d-2$, $d-1$, $d+1$, $d+2$, $d+3$. Estimates of daily species composition from the smoothed total daily catches of these three anadromous species were used to apportion hydroacoustic counts.

Agency species composition sampling

Data from this study were compared to other programs which monitor fish populations in the Roanoke River. Angling for Hickory shad and striped bass are the major

spring-time recreational fisheries in the upper river, and qualitative comparisons were made for both years between this study and a creel survey program. Biologists from the North Carolina Wildlife Resources Commission (NCWRC) interviewed recreational anglers in the upper river between 1 March and 31 April, 2004 and 1 March and 5 May, 2005. Creel samplers requested effort and catch information from randomly chosen anglers at three boating access areas in the upper Roanoke River (Gaston, Weldon, and Edward's Ferry). Daily catch per angler hour was compared to 2004 gill netting and 2005 electrofishing catch per unit effort from this study.

The NCWRC creel survey does not provide useful information about American shad. Even though they are occasionally caught by hickory shad anglers (Kornegay and Thomas 2004b), catches are not common enough to characterize seasonal progression. The creel survey also ends with the close of striped bass harvest (usually 30 April), which is relatively early in the American shad spawning season.

For 2005, American shad catches from this study were qualitatively compared to a Dominion electrofishing survey on what are considered the primary spawning grounds in the Roanoke River (Dominion 2006). Dominion biologists monitored a Roanoke Rapids site between the Route 48 bridge and a downstream bridge owned by the International Paper Company. The electrofishing methods used by Dominion differed from this study in several important ways. Most notably, Dominion used two netters generated current in pulses (20 seconds on, 10 seconds off), and sampled until they had captured 40 individuals. Dominion's voltage setting was higher (1000 vs. 680 v), and their pulse frequency (60 vs. 120 pps) and amperage (2.5-3.5 vs. 4.0 amps) were lower than in this study. Their crew sampled once weekly between 19 April and 26 July, 2005.

Hydroacoustics

The hydroacoustic system consisted of a shore-based DT-X digital echosounder, a connecting 70-m cable, and a 430 kHz 7-degree circular split-beam transducer (Biosonics, Inc.). In addition, a laptop computer provided an interface between the user and the hydroacoustic system. The echosounder was housed in a structure above the high-water mark, where it was connected to 120-volt AC current and backed up by a 12-volt deep cycle DC battery. The transducer and a remotely operated motor which controlled the transducer pitch angle were mounted on a submerged custom-fabricated aluminum frame (Figure 1).

In 2004 the deployment site was chosen after obtaining local bottom profiles. It was necessary that the cross-sectional river bottom be clear of irregularities (i.e., no debris or troughs along the bottom where fish could move without being detected), and this was verified by deploying the hydroacoustic gear in a downward-looking orientation before the field season in both years. The sample site had a minimum bank width of 80 meters. The transducer was lowered by boat to the river bottom, approximately 6 m off-bank from the 1 April, 2004 waterline, and in both years was oriented perpendicular to downstream flow. In 2005 the transducer was returned to the same approximate position.

During sampling, pings were emitted from the transducer face at a rate of 10 per second. The duration of each ping was 0.2 milliseconds. Sampled range extended 30 m from the transducer. Because this was a relatively “noisy” environment and because target strengths of fish target species were roughly -45 dB and greater (Love 1977), we set a threshold of -50dB for recorded echoes. With few exceptions, data were collected 24 hr per day and stored on a laptop computer. Each day the acoustic beam pitch angle was recorded after adjusting by remote motor so that the beam was aligned along the river bottom with

minimal interference. A water temperature setting within the operating software was updated to adjust for change in the speed of sound. Data files were stored in 20-minute increments, and backed up to additional file storage as necessary.

The hydroacoustics gear was calibrated by the manufacturer prior to the 2004 field season and by the author on Roanoke Rapids Lake prior to 2005 sampling. For the 2005 calibration, a standard 17-mm tungsten calibration sphere was suspended 7 m below a vessel platform, at a site with a water depth greater than 10 m. Observed and expected values were deemed sufficiently close so that no adjustment of target strength values was necessary during post-processing and analysis.

Data files were post-processed within the software package Echoview, version 3.25.55 (SonarData, Pty Ltd). The basic approach is to count “tracks” of individual upstream-migrating fish. Potential fish tracks that showed upstream movement (based on changes in horizontal angular position, Figure 6), were isolated manually and post-processed using a fish tracking algorithm. Within Echoview’s software environment, single target detection and fish tracking parameters were chosen with the assistance of Don Degan, Aquacoustics, Inc. (Appendix Tables 1-2).

In order to meet fish track requirements, a sequence of echoes had to follow a predicted trajectory with consistent changes in position and velocity. The algorithm for evaluating the trajectory was originally developed for missile tracking (Blackman 1986, Sonardata 2006) and uses two parameters (alpha and beta) to adjust the degree to which position and velocity can vary within a track along each of three axes (Figure 1). Additionally, two target gate settings defined how restrictive the algorithm was regarding nearby individual echoes. The settings are used to create a volume around the predicted

trajectory. Candidate echoes must fall within that volume in order to be added to an existing fish track. Less variation is allowed in range than in the major and minor axes. In order for a track to be accepted, a minimum of six single echoes had to be present, with gaps in time no larger than five single pings.

For tracks that met all criteria, measurements of target strength, range from transducer, duration in beam, horizontal direction (upstream vs. downstream), tortuosity, and angles of deviation from the beam axes were output for each echo within a fish track. All analyses in this study were based on average values for all echoes within a fish track.

Target strength is a commonly sought value in hydroacoustic research. In riverine studies it is a measure of the energy returned from a single acoustic target (reported in decibels, dB). The value is calculated from initial and returned echo intensity. For relatively small acoustic targets like single fish, very little of the energy which strikes the target will return. Therefore, target strengths are reported in logarithmic form. The equation for target strength is:

$$10 * \log_{10} \left(\frac{I_{bs}}{I_{inc}} \right)$$

where,

I_{bs} = the intensity of the backscattered wave and

I_{inc} = the intensity of the transmitted wave (or energy striking the target)

(Simmonds and MacLennan 2005). To illustrate, if $I_{bs} = I_{inc}$ then the ratio is one, the $\log_{10} 1 = 0$, and the target strength would be $10 * 0 = 0$ dB (i.e., a perfectly reflective target). In this

study, we might expect a single fish target to return $1/1000^{\text{th}}$ of the energy that strikes it. In

that case,
$$\frac{I_{bs}}{I_{inc}} = \frac{1}{1000},$$

$\log_{10} \frac{1}{1000} = -3$ and the target strength would be $10 * -3 = -30$ dB. The uncompensated target strength is affected by target reflectivity and the position of the target within the beam. Compensated target strength, which was used for all analyses in this study, is adjusted for beam position and is the predicted target strength if the target had been centered on the axes. As all three target species are known to overlap in length, we hypothesized that compensated target strengths would be normally distributed when pooled by year. The hypothesis was tested by fitting a normal curve to target strength data for each year, and evaluating goodness-of-fit (Shapiro-Wilks W or Kolmogorov-Smirnov-Lillifors D test ; JMP 5.1.2, SAS Institute 2006)

Range is defined as the distance from transducer face to target, measured in meters. The number of detected targets should increase as range increases, because the insonified cone increases in diameter with range. If fish are evenly distributed across the river channel, there should be a linear relationship between the logarithms of range and count of fish tracks at range due to the spherical spreading of sound (Brandt 1996). This assumption was tested by linear regression.

To exclude targets moving in a downstream direction, analyses were restricted to fish tracks with a horizontal direction between 45 and 135 degrees. These values are dependent on transducer orientation, but in our situation, a fish track with a horizontal direction of 90 degrees would be traveling directly upstream, parallel to the beam's horizontal reference. Tortuosity is a measure of deviation from a vector of direct upstream travel. It is calculated

as the total distance between all echoes in a track, divided by the straight-line distance from first to last echo. Duration in beam is measured in seconds, with greater time representing a slower swimming target. Angles of deviation from the beam axes, measured in degrees, may be positive or negative values, and were output as separate horizontal and vertical components.

Additional variables were computed for each fish track: elevation, distance off-bottom, and acoustic beam height in dB, degrees and meters. Fish track elevation (Don Degan, personal communication) in m was:

$$= -2.2 + r * SINE(p + v_angle)$$

where,

r = mean range for a fish track

p = mean daily transducer pitch

v_angle = mean vertical angle of deviation for a fish track.

Because our transducer was deployed close to the river bottom, it was mounted in the frame in an upside-down orientation. We accounted for this by changing the sign on all observations of vertical angle.

The transducer was at a depth of 2.2 m on the day of first deployment, and that value was used as a benchmark for calculations in both years. Bottom elevation (from the GIS survey) at range r was subtracted from fish track elevation to yield a distance off-bottom for each fish track.

Acoustic beam height was dependent on range and the acoustic size (target strength) of each upstream migrating fish, because a large fish may be detected further off the beam

axis than a small fish. The distance off the beam at which a fish can be detected is based on the sonar equation (Brandt 1996):

$$EL = SL - 2TL + TS + 2B(\theta)$$

where the returning echo level (EL) is determined from the source level (SL) of the transmitted sound, transmission loss (TL) that occurs with range, target strength, and the beam pattern ($B(\theta)$). For a target at a given range, the source level and transmission loss would be constant so detection of the target would depend on TS and $2B(\theta)$. Beam height in dB was calculated as the difference between target strength threshold (-50dB) and the mean target strength for each fish track, divided by two. Beam height in degrees is calculated based on the beam pattern provided by the manufacturer. That pattern shows the decline in transducer sensitivity as a function of angle “off-axis.” For the transducer used in this study, fish with target strength of -30 dB would have a beam height of -10 dB, or 10.97 degrees according to the transducer sensitivities provided by the manufacturer. A measure of beam height in meters must consider range:

$$= 2 * r * TANGENT\left(\frac{b}{2}\right)$$

where,

r = mean range for a fish track

b = beam width in degrees

For the hypothetical fish, a beam height of 10.97 degrees results in a beam height of 1.92 m at a range of 10 meters.

It was hypothesized that hydroacoustic variables would associate with each other in meaningful ways, and this was tested by computing nonparametric Spearman rank correlations (Zar 1999). For example, correlation was examined between date and target

strength to test for a (linear) seasonal change in mean target strength. It was thought that mean target strength would increase during the anadromous season due to the increased frequency of striped bass, which are expected to be a larger acoustic target than hickory shad.

The approach used in post-processing the 2004 data was to select a systematic sample of files from every day between 3 April and 31 May, 2004. A 5-minute file segment was post-processed from each of four periods throughout the day (00:00, 06:00, 12:00 and 18:00). On six of 55 days, additional files were post-processed to investigate increasing post-processing effort. Additional systematic fractions of available files were examined on 8, 20, 21 and 26 April; 2 and 26 May. The additional days were selected during periods of higher suspected migration, and were included in run size estimation.

For 2005, a larger subset of each day's data was post-processed, and files were selected using three 8-hr periods (strata). A stratified random sample of three 20-minute data files was drawn from within each stratum, totaling nine files for each day. Having three randomly selected files within each stratum made it possible to calculate point estimates and variance estimates for each day. Based on a stratified random sampling method, the number of fish (for a particular species) that migrated upstream past the monitoring site on day i (\hat{N}_i) was estimated as:

$$(1) \quad \hat{N}_i = \hat{S}_i \hat{C}_i^*$$

where, on day i ,

\hat{N}_i is the estimate of the total number of upstream migrating fish,

\hat{C}_i^* is the count (expanded by space and time) of upstream migrating fish, and

\hat{S}_i is the proportion of the count comprised by a target species.

An estimate of run size for the target species is therefore obtained by:

$$(2) \quad \hat{N}_{run} = \sum_{i=1}^R \hat{N}_i$$

where,

\hat{N}_{run} is the estimate for run size, and

R is the number of days sampled in a season.

We divide each day into $k = 1, \dots, 3$ independent time strata of 8 hr each and divide each time stratum into $l = 1, \dots, N$ independent time units of 20 minutes each ($N = 24$). Daily count is further explained by:

$$(3) \quad \hat{C}_i^* = \frac{\hat{C}_i}{\alpha_s}$$

where \hat{C}_i^* expands the count on day i by the spatial sampling fraction α_s . The spatial sampling fraction α_s is an adjustment to account for the linear proportion of the river width unsampled by the beam, and assumes that the sampled river fraction is representative of the unsampled fraction. By this method we also assume the effects of changing river flow on cross-sectional area are negligible. The hydroacoustic gear sampled 29.5 of 80 m ($\alpha_s = 0.3688$) in both years.

Three strata were post-processed within each day, and \hat{C}_i is defined as the sum of counts on day i :

$$(4) \quad \hat{C}_i = \sum_{k=1}^3 \hat{C}_{ik} .$$

Three 20-minute data files were post-processed within each 8-hr stratum:

$$(5) \quad \hat{C}_{ik} = \frac{\sum_{l=1}^3 \hat{C}_{ikl}}{\alpha_{ik}}$$

where \hat{C}_{ik} expands the sum of counts within a single stratum k by the temporal sampling fraction α_i . The temporal sampling fraction α_{ik} for day i is the proportion of the 8-hr period k for which acoustic data were post-processed. In 2005 sampling the temporal fraction was identical for all strata in all days, and so here we drop the ik notation.

The estimated total number of upstream migrating fish in a randomly sampled time unit l within stratum k on day i is defined as:

$$(6) \quad \hat{C}_{ikl} = \sum_{j=1}^{n_{ijkl}} \frac{D_{ijkl}}{2r_{ijkl} \tan\left(\frac{b_{ijkl}}{2}\right)}$$

where r_{ijkl} is mean range for fish track j , D_{ijkl} is mean river depth in meters on day i at range r_{ijkl} for fish track j , and b_{ijkl} is beam width in degrees for fish track j (Skalski et al. 1993).

The expression $2r_{ijkl} \tan(b_{ijkl}/2)$ provides beam width in m. The ratio following the summation sign (river depth divided by beam width) adjusts each counted fish upwards to account for the fraction of the water column not covered by the beam. This method assumes an even distribution of targets within the vertical water column.

The model for estimated fish passage by day can be resummarized as:

$$(7) \quad \hat{N}_i = \hat{S}_i \frac{1}{\alpha_s} \sum_{k=1}^3 \frac{1}{\alpha_t} \sum_{l=1}^3 \sum_{j=1}^{n_{ijkl}} \frac{D_{ijkl}}{2r_{ijkl} \tan\left(\frac{b_{ijkl}}{2}\right)}$$

where the terms α_s and α_t may or may not be treated as constants. In 2004, $\alpha_s = 0.3688$ and α_t was variable. In 2005 sampling $\alpha_s = 0.3688$ and $\alpha_t = 0.1250$ for the entire field season.

If α_s and α_t are constant, the variance of the product \hat{N}_i is estimated by:

$$(8) \quad \text{Var}(\hat{N}_i) = (\hat{S}_i \hat{C}_i^*)^2 \left[\frac{\text{Var}(\hat{C}_i^*)}{(\hat{C}_i^*)^2} + \frac{\text{Var}(\hat{S}_i)}{(\hat{S}_i)^2} \right]$$

(modified from variance estimator in Williams et al. 2002). Variance for seasonal fish passage estimates by species can be estimated as:

$$(9) \quad \text{Var}(\hat{N}_{run}) = \sum_{i=1}^R \text{Var}(\hat{N}_i).$$

As we calculate it, the variance of \hat{C}_i^* ignores spatial variability across the river cross-section, rather treating it as a constant, and is defined as:

$$(10) \quad \text{Var}(\hat{C}_i^*) = \frac{\text{Var}(\hat{C}_i)}{\alpha_s^2}.$$

The variance of \hat{C}_i is estimated as the sum of variances across strata on day i :

$$(11) \quad \text{Var}(\hat{C}_i) = \sum_{k=1}^3 \text{Var}(\hat{C}_{ik})$$

and the finite population sampling variance of a population total is

$$(12) \quad \text{Var}(\hat{C}_i) = \sum_{k=1}^3 N_{ik} (N_{ik} - n_{ik}) \frac{s_{ik}^2}{n_{ik}}$$

(Cochran 1977). Assuming a constant temporal sampling fraction (3 of 24 20-minute files), the estimated variance for the total daily count within the 29.5 m monitored by the hydroacoustic gear would be:

$$(13) \quad \text{Var}(\hat{C}_i) = \sum_{k=1}^3 24(24-3) \frac{s_{ik}^2}{3}$$

where,

$$(14) \quad s_{ik}^2 = \frac{\sum_{l=1}^3 (\hat{C}_{ikl} - \bar{\hat{C}}_{ik})^2}{3-1} .$$

Variation within a stratum is represented by the standard empirical sample variance s_{ik}^2 (Sokal and Rohlf 1981), which incorporates hydroacoustic measurement error and sampling error (Skalski et al. 1993).

To estimate the variance of \hat{S}_i for a target species we apply the proportional quantity from the 7-day moving average in a binomial approximation:

$$(15) \quad Var(\hat{S}_i) = \frac{\hat{S}_i(1-\hat{S}_i)}{n}$$

where n is the sum of target species captured on sample days $d-3$, $d-2$, $d-1$, d , $d+1$, $d+2$ and $d+3$.

This expansion method assumes fish tracks were homogenously distributed in the vertical water column (Skalski et al. 1993; Don Degan personal communication). Strata within day i were assumed to be independent, and daily counts were assumed to be independent. Species proportions from a 7-day average were assumed to represent the population of anadromous species migrating past the study site on that day.

Fish passage estimates which incorporate temporal replication by 8-hr strata allow for an evaluation of diel periodicity. For 2005 we tested the null hypothesis that there is no difference in mean upstream fish passage across the three time strata. Count values were log transformed to satisfy the assumption of normality and equality of variance (Zar 1999).

Count data (\hat{C}_{ik}) means were tested by analysis of variance and the Tukey Honestly

Significant Difference test for unequal samples (Zar 1999). Days without equal sample sizes from all strata were removed (n = 6).

In addition, it was hypothesized that hydroacoustic monitoring would correlate with two independent data sets. The relationship between daily estimated hydroacoustic abundance and target species abundance in electrofishing samples was tested by nonparametric Spearman rank correlation. Daily hydroacoustic estimates were also compared to mean daily flow by the same method. Samples from identical dates were assumed to be independent.

Target strength investigations

The target species in this study were expected to overlap in physical size. To compare the differences between mean total length of American shad, striped bass and hickory shad, we used analysis of variance and the Tukey Honestly Significant Difference test for unequal samples (Zar 1999). Analyses assumed that individuals come from a population whose lengths are normally distributed. For this general purpose, lengths from species composition sampling were pooled for both years.

Equations for predicting target strength as a function of fish size vary depending on fish orientation and species. A general equation for individual fish at any aspect was provided by Love (1977). For a transducer frequency of 420 kHz, the equation is:

$$\text{Target Strength (dB)} = 20 * \log_{10}(\text{fish length in cm}) - 69.23 .$$

Based on this equation, a 15-cm fish would have a predicted target strength of -45.7 dB. We plotted the predicted target strength for all three target species and for both gears. Hartman and Nagy (2005) provide an equation to predict the target strength of striped bass in the dorsal aspect for a 120 kHz transducer. Despite the differing orientation and frequency, we

also plot the expected target strengths to compare predicted target strength distributions for both equations. The equation for striped bass from Hartman and Nagy is:

$$\text{Target strength (dB)} = \text{TS} = 15.37 \log_{10}(\text{fish length in cm}) - 56.47 .$$

Based on this equation, a 15-cm fish would have predicted target strength of -38.4 dB.

An experiment was done on 16 and 22 June, 2005 in order to investigate the empirical relationship between target strength and fish length for American shad. Fish were collected by boat electrofishing on the spawning grounds just downstream of the Route 48 bridge in Roanoke Rapids, following standard electrofishing methods outlined previously. Individuals were anesthetized using clove oil, and suspended within a 3-m square frame constructed of 2.54-cm-diameter PVC pipe. Monofilament tethers were anchored at the four corners of the frame, and connected to each specimen by small commercially available fishing hooks (#20), following the methods of Hartman and Nagy (2005). The transducer was deployed at a water depth of 1 m and aimed manually. Each specimen was centered on the acoustic beam axis, and insonified in side-aspect at a range of 6-9 m for approximately 2000 pings. The hydroacoustic system settings matched those used in the 2004 and 2005 anadromous monitoring seasons.

Target strengths were recorded for two male and two gravid female American shad. It was hypothesized that the variation in acoustic size of a target could be explained by its physical size. This was tested using linear regression of mean target strength versus total length. As target strength is reported in logarithmic form (-dB), we converted individual target strengths to estimates of acoustic spherical-scattering cross-section (σ) before calculating the mean and standard deviation for each fish (Foote 1980):

$$\sigma = 4 \pi 10^{TS/10} .$$

The mean and standard deviation may then be calculated, and converted back to target strength by:

$$TS = 10 \log \left(\frac{\sigma}{4\pi} \right).$$

Alternate run size estimates

Four alternate run size estimates for 2005 were calculated using different assumptions about the cross-channel distribution of fish and the ability to detect fish tracks at different distances from the transducer. The objective was to examine the sensitivity of the run size estimates to these changes.

The present run size model was referred to as the null model (R_0), because of the simple assumptions being made regarding cross-channel fish distribution and target detection. Fish tracks were assumed to have a homogenous vertical distribution, and there was a simple expansion from fish tracks within the beam height to the entire water depth. In addition, the linear range sampled by the hydroacoustic gear was assumed to be representative of the unsampled river fraction, and all fish tracks were assumed to be detected.

The first alternate run size estimator (R_1) assumed that upstream migrating fish were not reliably detected beyond an effective range of 15 m. This alternative was developed after inspecting the cross-channel distribution of fish tracks (see Results, Figure 18). Because fish tracks beyond 15 m were assumed to have an unknown but lower probability of detection, the run size estimate was obtained by expanding from a sampled range of 14.5 m (vs. 29.5 m for method R_0) to the entire river width (80 m). Variance calculations utilized only fish tracks with a range between 0.5 m and 15 m, and were identical to method R_0 .

The second alternate estimator of run size (R_2) used the same assumption of a 14.5-m effective range as R_1 but also assumed that fish tracks had a different density in the first meter off bottom compared to the remainder of the water column. Fish tracks detected less than or equal to 1 m from the river bottom were not expanded to the entire river depth, under the assumption that expansion was inappropriate due to a behavioral aggregation of fish targets near the river bottom. Fish detected greater than 1 m from the bottom were expanded vertically to the remainder of the water column using method R_0 . Variance calculations were adapted to include the additional level of stratification (i.e., day, 8-hr period, distance off-bottom \leq or $>$ 1). All variance components were summed by day per method R_0 . We acknowledge that this run size estimator would have a slight negative bias. Due to beam geometry, fish migrating within approximately 3 m of the transducer and at an elevation greater than 1 m off-bottom were unavailable to detection. There could be neither count nor expansion of undetected individuals to the full water column height for the range 0.5 to 3m.

In contrast to methods R_1 and R_2 , the third alternate estimator of run size (R_3) assumed the horizontal expansion from sampled range to river width was inappropriate, and that bank habitat was to be treated differently than mid-channel habitat. The density of fish tracks within the 14.5-m range sampled by the beam was assumed to be reliably determined and to characterize the first 21 m from shore (15 m + 6 m between shore and the transducer frame) on both the north and south banks. This method essentially expanded the sampled range from 14.5 m to 42 m. Fish detected at a range of between 15 and 30 m range were assumed accurate for the mid-channel habitat, and were adjusted to the remaining unsampled range (38 of 80 m). Variance components were calculated separately for the bank habitat

(based on an expansion from 14.5 to 42 m) and the mid-channel habitat (based on an expansion from 15 m to 38 m). The two variance components were summed by day

The final alternate run size estimator (R_4) was based on method R_3 , but included a species-specific adjustment in the expansion factor in order to account for differences between the two banks. This method assumed that disparity between 2005 electrofishing catch rates for each bank was biologically correct, and should be reflected in daily fish passage estimates. The 7-d moving average of electrofishing catches was again used to apportion fish tracks by species for each bank. North bank estimates were then adjusted by a smoothed ratio of catch rates between banks (again, smoothing the ratio by 7-day moving average). For example, if on a sample day twice as many striped bass were captured on the north bank than the south, the south bank hydroacoustic fish passage estimate for the 21-m range nearest shore was multiplied by a factor of two to estimate north bank fish passage. Fish detected at a range of between 15 and 30 m range were treated as in method R_3 . A variance calculation has not been developed for this method.

RESULTS

River environment

River temperature exhibited a similar increasing trend in both years of study, as is expected in a southeastern coastal river system during the spring season (Figure 7). Values ranged from 6.3 - 25.9°C in 2004, and 5.7 – 21.6°C in 2005. The trend for both years is consistent with the 8-yr average of mean daily water temperatures at the Halifax gage site. Water temperature reached 18°C on 27 April, 2004 and 12 May, 2005.

Mean daily flow averaged 190 m³s⁻¹ (6,721 ft³s⁻¹) in 2004, and 264 m³s⁻¹ (9,313 ft³s⁻¹) in 2005. Mean flows during both years were within the range 144-276 m³s⁻¹ (5,091-9,741 ft³s⁻¹), defined by Hassler et al. (1981) as “low to moderate” and considered good conditions for striped bass spawning (reported in Rulifson and Manooch 1990). However, high discharge periods were recorded in both years. Mean daily flow was greater than 283.2 m³s⁻¹ (10,000 ft³s⁻¹) during three periods: 15 April – 27 April, 2004; 19 March – 22 March and 29 March – 10 April, 2005.

There was a significant linear relationship between daily mean river stage at the Halifax gaging station and mid-channel depth measurements made at the transducer site ($R^2 = 0.95$, $p < 0.001$). Based on this relationship, daily mean mid-channel depth at the transducer site was predicted for both 2004 and 2005 (Figure 7). In April and May, 2004 mid-channel depth at the transducer ranged from 1.7 to 5.9 meters. From 4 March through 4 June 2005 depth ranged from 3.3 to 7.4 meters. The relationship between mean daily flow at the Roanoke Rapids Dam gaging station and mid-channel depths was also significant ($R^2 = 0.92$, $p < 0.001$).

Species composition sampling

Twenty-nine fish species were captured by gillnetting and electrofishing during the 2004 and 2005 field seasons (Tables 1-2). The most numerous species captured by all gears were striped bass and hickory shad. American shad made up 1.8% of catches for both years. Although the primary sampling gear switched from gill netting to electrofishing between years, the anadromous target species (American shad, striped bass, hickory shad) were a consistently high percentage of the total catch, comprising 69% in 2004 and 60% in 2005. If bank electrofishing samples (which capture a wide range of resident species) are excluded, the three anadromous species comprised 86% of gill-net and 87% of channel electrofishing catches in 2004 and 95% of gill-net and 83% of channel electrofishing catches in 2005.

Thirteen species of fish were captured by gillnetting in 2004 and 2005 (Tables 1-2). The most numerous species captured were striped bass and hickory shad in 2004, and striped bass and American shad in 2005. The 10-cm stretch mesh size was most effective in both years, followed by the 7- and 14-cm-mesh sizes respectively (Tables 3-4). Catches were lowest when mean daily river depth was greater than 4.6 meters, corresponding to “high” river flows of $283 \text{ m}^3 \text{ s}^{-1}$ ($10,000 \text{ ft}^3 \text{ s}^{-1}$) or greater (Rulifson and Manooch 1990). Occasional fouling of gill nets by aquatic plants and algae during drifts also appeared to contribute to catch success and variability.

In 2004, systematic gill-net sampling was more comprehensive than electrofishing and documented a transition in dominance from hickory shad to striped bass during the anadromous season (Figure 8). Hickory shad were captured on 15 March (mean daily temperature 10.1°C) when sampling was initiated. Greatest catch per unit effort (CPUE) was observed on 31 March ($1.9 \text{ individuals} / 100 \text{ m drift}$, 12.6°C) then declined gradually until

disappearing from catch records. Hickory shad were last captured on 24 April (17.4°C). In contrast, striped bass were absent from catches until 21 March (11.4°C) and last captured on 24 May (25.5°C). Striped bass CPUE peaked on 12 May (6.3 individuals / 100 m drift, 21.5°C). American shad were captured infrequently (n = 5) between 31 March (12.6°C) and 8 May (20.0°C), and comprised 1% of the total catch and 1% of the targets species catches.

American shad had a mean total length (\pm SD) of 485 mm (36) with a range from 450-537 mm. Hickory shad had a mean total length of 445 mm (\pm 22) with a range of 398-502 mm. Striped bass had a mean total length of 478 mm (\pm 43) with a range of 372-629 mm (Figure 9).

In 2004 systematic gill-net sampling captured fish during all four-hour periods in a day. We tested the null hypothesis that numeric catches would not differ significantly across 4-hr periods. Assuming catches in each time block were independent, hickory shad catches were consistent with the hypothesis at the 5% significance level ($\chi^2 = 2.41$, df = 5, p = 0.79), as were striped bass catches ($\chi^2 = 3.67$, df = 5, p = 0.60). A significance test was not done for the five American shad sampled by gillnetting, which were encountered at erratic times (00:32, 01:25, 09:14, 11:10, and 15:01).

Gill net catches for 2005 (Table 4) were much lower, and were not used to apportion hydroacoustic counts of upstream migrating fishes as they were in 2004. The drift distance was doubled to 200 m, yet catches did not increase. Hickory shad were once again first captured on 15 March (7.9°C), and last captured on 12 April (13.1°C). Greatest CPUE was observed on 12 April (0.3 individuals / 100 m drift). Striped bass were absent from catches until 12 April (13.1°C) and last captured on 4 June (20.6°C), the final day of species composition sampling. Striped bass CPUE peaked on 24 May (3.6 individuals / 100 drift,

19.7°C). American shad were captured infrequently ($n = 15$) between 21 April and 25 May, and comprised 8% of the total, and 9% of the species of target species catches.

Throughout the field season the height of gill nets was adjusted to best sample the channel from water surface to river bottom. In 2005 58% of target species were captured within one meter of the leadline, and 85% were captured within two meters (Table 5). The dominance of striped bass catches contributed most to the percentages (81%). Although a drifted net is not always parallel to the river bottom, we consider distance from leadline to be a proxy for distance off-bottom. As mean water depth was never less than 3.3 m, and largely greater than 4 m, we characterize these results as a consequence of behavior.

Twenty-nine fish species were captured by electrofishing in both years (Tables 1-2). The most numerous species captured were striped bass and hickory shad. The species diversity of bank transects was very different from samples in the center channel. In both years, samples from the north bank exhibited greatest abundance and diversity.

The 2004 electrofishing catches (Table 6) were in general agreement with gill-net run timing. Hickory shad were captured from 11 March to 15 April. Striped bass were captured on 29 April and 12 May, but absent on 26 May. Four American shad were captured by electrofishing, all after 29 April. Because of the low level of sampling and a change to a new electrofishing boat on 29 April, electrofishing data were not used in making the 2004 run size estimates.

In 2005 electrofishing best captured the transition in dominance from hickory shad to striped bass (Table 7). Between 14 April and 26 April we detected a gradual decline of hickory shad and a reciprocal increase in striped bass abundance (Figure 10). Hickory shad were captured on 9 March when sampling was initiated. Greatest CPUE for hickory shad

was observed on 29 March (74 individuals / 2700 seconds of shock time, 10.2°C) then declined gradually until absent from catch records. Hickory shad were last captured on 26 April, (14.3°C). Striped bass were absent from catches until 14 April (13.1°C) and last captured on 4 June (20.6°C) when the study ended. Striped bass CPUE peaked on 30 May (72 individuals / 2700 s, 21.2°C). American shad also increased in frequency as the migratory season progressed, and comprised 2% of total and 3% of the target species catches. They were first captured on 15 March (7.9°C), but catches remained sporadic until late May. American shad catch peaked on 18 May (7 individuals / 2700 s, 19.4°C), and continued until sampling ended on 4 June (20.6°C).

American shad had a mean total length of 424 mm (± 40) with a range of 373-572 mm. Hickory shad had a mean total length of 418 mm (± 50) with a range of 222-511 mm. Striped bass had a mean total length of 476 mm (± 67) with a range of 190-1050 mm (Figure 11). A distinct group of very small striped bass ($n = 14$, range 190-247 mm) were captured near the end of May, and were found to be immature.

Length frequencies of striped bass were not significantly different between years ($D = 0.06$, $p = 0.28$). Though it is inadvisable to compare catches between gears, the similarity between fish lengths in 2004 and 2005 are important for discussion of expected acoustic target strengths.

Agency species composition sampling

The timing of migration for hickory shad in 2004 appeared similar based on gill-net catches and NCWRC creel survey estimates of catch per angler hour (Figures 8, 12). Gill netting first detected hickory shad when sampling was initiated on 15 March. The NCWRC program first interviewed successful anglers on 6 March. Both programs consistently

sampled hickory shad between 15 March and 12 April. Hickory shad were last detected by angler interview on 14 April, and by gill-net sampling on 24 April.

There was less agreement between 2004 surveys for striped bass (Figures 8, 13). Anglers were first successful for striped bass on 16 March, and catch success greatly improved after 5 April. Peak success was 3.1 striped bass / angler hour on 5 April, followed closely by 2.8 striped bass / angler hour on 22 April. Mean daily water temperature reached 18°C on 27 April, 2004. Gill-net catches of striped bass were low until 8 May, and did not peak until after the cessation of NCWRC creel sampling. Given the high angler catch rates during April, it is clear that gillnetting was relatively ineffective during that time. In addition, the electrofishing efforts on 29 April verified the presence of striped bass (21 striped bass / 2700 s). River flows greater than 283.2 m³s⁻¹ (10,000 ft³s⁻¹) between 16 April and 26 April likely contributed to the ineffectiveness of gill-net sampling. However, another possible interpretation is that anadromous fishes could have moved out of mid-channel habitat and closer to shore during the period of high flows. Though the availability of fish to gill-net sampling and angling is not the same, lack of qualitative agreement between striped bass presence was a major concern, and contributed to making electrofishing the primary sampling gear in 2005.

In 2005, electrofishing CPUE had better agreement with NCWRC data for both dominant anadromous species (Figures 10, 14-15). Hickory shad were recorded by both surveys from 9 March to 23 April, and were absent from both surveys after 26 April. NCWRC biologists first interviewed successful striped bass anglers on 9 April, and electrofishing first detected striped bass presence on 14 April. Striped bass were detected in all samples by both surveys until the angler interview program ended on 5 May.

Results from this study were generally consistent with a Dominion survey, regarding the timing of migration for American shad in 2005 (Figure 16). American shad were captured at Roanoke Rapids between 19 April and 26 July and in this study between 15 March and 4 June when sampling ended. Though the distance between sites is significant (26 rkm), it is noteworthy that peak CPUE for both surveys were within the same week. It is expected that the Dominion study would continue to detect American shad on the spawning grounds through a portion of the summer.

Hydroacoustics

Digital data were collected from 3 April - 31 May, 2004 (64 gigabytes), and 9 March - 3 June, 2005 (99 gigabytes). On 13 April, 2004 a malfunction in the transducer cable required that the equipment be removed from the river and returned to Biosonics for repair. The equipment was redeployed on 16 April at the same approximate location. On seven other occasions the echosounder stopped transmitting even though power to the system was intact (2-3 May and 19-20 May 2004; 11 April, 16 April, 30 April, 1 May, and 6-7 May 2005). Inclement weather was noted during four of seven incidents. In all cases, the problem was discovered within 16 hr, and a reboot of the system corrected the problem.

Mean target strengths for individual upstream-migrating fish varied widely, ranging from -13.2 to -45.3 dB in 2004 and from -15.9 to -45.3 dB in 2005 (Figure 17). The distributions were similar in 2004 (mean = -29.6 dB, standard deviation 4.9 dB, median -29.2 dB) and 2005 (mean = -30.7 dB, standard deviation = 4.8 dB, median = -30.7 dB). The distribution for 2004 failed a goodness-of-fit test for normality ($p < 0.001$); however, data from 2005 were consistent with a normal population ($p = 0.09$).

Upstream-migrating fish were not distributed uniformly within the channel cross-section (Figure 18). In 2004, 50% of fish tracks were detected at a range between 9-19 m. In 2005 50% of fish tracks were detected at a range between 5-14 m. There was no significant linear relationship between the logarithms of range and count of fish tracks in either year, which would be expected if fish were uniformly distributed within the hydroacoustic beam and across the channel. Instead we found a significant negative rank correlation between range and fish counts (2004: $r = -0.82$, $p < 0.001$; 2005 $r = -0.96$, $p < 0.001$), indicating that fish were more associated with ranges near shore. Most fish tracks were estimated to be close to the river bottom (Figure 18). In 2004, 87% of fish tracks were within one meter, and 98% were within two meters of the river bottom. Fish which had negative values for distance off-bottom were included in the category 0-1 m from bottom. In 2005 67% of fish tracks were within one meter, and 86% were within two meters of the river bottom (Table 8). For both years combined, 89% of fish tracks were within two meters of the estimated river bottom.

For the remaining acoustic variables, there were few meaningful rank correlations. There was a weak significant negative correlation between compensated target strength and date for 2004 ($r = -.19$, $p < 0.0001$) but the relationship was not significant for 2005. Duration in beam, tortuosity, and deviation from the beam axis had significant but very weak, or no rank correlations, with date and do not provide valuable information for discussing change in acoustic variables as a function of season.

Upstream migrant counts varied considerably from day to day but showed some seasonal patterns (Tables 9-10, Figures 19-20). The initial daily estimates of upstream migrants in 2004 were quite high because monitoring did not begin until early April (Figure

19). The estimates declined rapidly as the hickory shad run ended. Two later peaks were predominately striped bass based on species composition sampling (Figure 21). A large run of hickory shad was not observed in 2005 (Figure 22). Daily estimates of upstream migrants gradually increased throughout the month of May, due primarily to striped bass. The 2004 estimate of total upstream migrating fishes was 284,289 individuals for the period 3 April to 31 May. Species-specific estimates are 9,046 American shad, 149,067 hickory shad, and 126,176 striped bass (Table 9, Figure 21). The 2005 estimate (and SE) of upstream migrating fishes was 156,098 (6,101) individuals. Species-specific estimates are 7,054 (450) American shad, 30,266 (2,981) hickory shad, and 118,778 (4,799) striped bass (Figure 22). Days for which data were missing due to equipment malfunction (10 of 142) were linearly interpolated.

In 2005, the mean number of upstream migrants per 20-minute interval was 6.1, 12.5 and 10.0 individuals for time strata 00:00-08:00, 08:00-16:00, and 16:00-24:00, respectively. Mean fish passage was significantly different by strata (ANOVA, $p < 0.0001$). Using Tukey's honestly significant difference test to compare all means, we found that upstream passage was not different between strata 08:00-16:00 and 16:00-24:00. Mean fish passage for stratum 00:00-08:00 was significantly less.

Using only dates in 2005 when daily estimated hydroacoustic fish passage and electrofishing species composition samples are both available ($n = 54$), there was a significant positive rank correlation ($r = 0.32$, $p = 0.02$) between the abundance counted by each gear (Figure 23). There was also a significant negative rank correlation between estimated hydroacoustic fish passage and mean daily river flow (2004 $r = -0.36$, $p < 0.01$; 2005 $r = -0.63$, $p < 0.0001$).

Target strength investigations

For the hickory shad, American shad, and striped bass captured during species composition sampling, predicted target strengths using Love's any-aspect equation varied widely. Most values were between -38 and -33 dB (Figure 24). There was considerable overlap in predicted target strengths for the three species. Predicted target strengths for striped bass only (Figure 25) were tightly centered around -36 dB using Love's equation and -30 dB using a dorsal-aspect equation developed for striped bass by Hartman and Nagy (2005). The observed target strength distributions from hydroacoustic monitoring were substantially more variable and on average exhibited higher mean target strength than would be expected from Love's equation (Figures 17, 24). The mean predicted target strength from Hartman and Nagy's (2005) equation was similar to the empirical values (2004: mean = -29.6 dB; 2005: mean = -30.7 dB).

There was a non-significant but linear relationship ($p = 0.11$) between fish length and mean target strength for four American shad experimentally suspended in the hydroacoustic beam (Figure 26). Target strength did increase with maximum total length, and a larger set of measurements may have provided the sample size required for significance. The size of American shad captured for the experiment ranged from 402 to 499 mm, which was within the mid-range of fish captured by electrofishing in 2005 ($n = 48$, 373 – 572 mm). Mean target strengths ranged from -32.6 to -27.3 dB.

Alternate run size estimates

By altering the assumptions of the run size model, estimates for all target species range between 126,662 and 585,661 upstream migrating fish (Table 11). Model R_4 yielded

the largest estimate by treating each bank and the mid-channel habitat separately and applying a ratio of abundance (north / south) to the north and south banks for each target species (Table 2). The estimate was largely affected by the high relative abundance of striped bass in north bank electrofishing catches. Run size estimates for striped bass ranged between 94,529 (SE=3,807) and 534,750 individuals. The low abundance and evenness in catches between banks for American shad affected little change on the seasonal estimate between model R_4 and the remaining models. Model R_2 produced the smallest estimate by truncating the sample range at 15 m and additionally stratifying fish tracks by elevation within the water column. The null model R_0 ranked as the second smallest estimate. American shad estimates (and SE) showed little variation, ranging between 5,422 (346) and 13,604 (887) individuals (Figure 27).

DISCUSSION

Potential of hydroacoustic monitoring

Hydroacoustic monitoring, in combination with traditional fish sampling, clearly documented the seasonal patterns of migration for the dominant anadromous species in the Roanoke River. The transition from hickory shad to striped bass in species composition samples occurred in late April to early May of both years. This was about the same time that daily numbers of upstream migrants started to increase rapidly. In both years, hydroacoustic estimates peaked during periods when the dominant species was about 90% of the target species catch. Peak striped bass and hickory shad catches also agree with the published range of expected arrival and spawning temperatures in North Carolina (reviewed in Burdick 2005). We conclude that our study successfully monitored relatively large pulses of upstream migrants.

There was not a well-defined peak for daily estimates of upstream-migrating American shad, because of their consistently low occurrence in species composition samples. The low abundance and absence of migration pulses is in contrast with results for the Delaware River, the site of the only other known hydroacoustic assessment of American shad in the eastern United States (PACE Environmental Services 2001, 2003). They use nine transducers to monitor river channels between bridge pilings, and estimate daily passage of American shad from mid-March through the end of May. Their estimates are obtained using echo integration of entire schools, rather than counting tracks of individuals as done here. Their Delaware River estimates for 1998-2003, except for 1999, all exceeded 250,000 individuals. The maximum daily migration for 2001 was over 200,000 fish, and greater than 16,000 fish in 2003.

Target strength as a measure of fish size

Target strength is an important hydroacoustic variable in that it is related to fish size (Simmonds and MacLennan 2005). A target strength threshold can be used to exclude noise and record only the stronger echoes that would be from fish greater than some minimum size. We established a threshold of -50 dB, which would be the expected target strength of a fish about 5 cm in length (Love 1977). Observed target strength distributions had modes of about -30 dB, which would be roughly the expected target strength of migrating striped bass. However, the distributions were much broader than would be expected if target strength values were a simple linear function of fish length (e.g., compare Figure 17 with 23-24). There are also more relatively high target strength values (>-25 dB, expected from fish 1.2 m or larger) than would be expected based on fish sampling. Although fish of that size are possible, another potential explanation for the high values would be if tracks for fish moving close to the bottom were contaminated by bottom echoes.

The estimates of run size for individual species do not rely on target strength (or any other acoustic variables) to determine the species of an upstream migrating fish track. Instead of assigning a species identifier to individual tracks, the total numbers of tracks within a day are apportioned among species based on the fish sampling. However, target strength is still an important potential source of error for run size estimates, in that it is used to estimate beam height (the insonified region used to expansion to the full channel cross-section).

Many factors can affect the accuracy and precision of measured target strength. One factor is orientation of the fish to the hydroacoustic beam, with the side-aspect orientation reportedly yielding highest acoustic reflectivity (Simmonds and MacLennan 2005). Kubecka

and Duncan (1998b) found, however, that acoustic size varied little in fish which were swimming directly upstream against a current, and concluded that variation in aspect angle was minimal when compared to open-water acoustic surveys. This should be relevant to our situation, as the mid-channel habitat was predominantly occupied by deliberately migrating species. There may also be seasonal changes in target strength due to changes in body composition. Ona et al. (2000) found that target strength varied seasonally for herring held in captivity. Values increased according to fat content and gonad development, increasing mean target strengths by up to 3 dB.

Position off-axis could be a significant source of bias in estimates of target strength. Fleischman and Burwen (2000) found that error in position estimates and a low signal to noise ratio strongly affected off-axis estimates of target strengths in split-beam studies. This was further discussed in Kieser et al. (2005). Effectively, the farther a target is off-axis, the more “noise” from the environment may be incorporated into the echoes from a fish track. This could explain some of the difference between observed target strengths and expected values based on laboratory trials (i.e., Love’s (1977) equation).

Another factor that can affect estimated target strength is when multiple targets are present within the beam at the same time (Cronkite and Enzenhofer 2002). Split-beam transducers can produce negatively biased target strengths when fish are aligned in the beam volume at different ranges, such that one shadows the other. Oppositely, when multiple fish targets are detected at the same range they exhibit additive, positive target strength bias. Fish tracks that could generate both kinds of bias were observed during the post-processing of files; however, the frequency of such events appeared to be rare and likely affects precision more than accuracy.

There is no indication that target strength could be used to distinguish species in the Roanoke River. As mean target strength can be a good estimator of mean fish size, we expected an increase in mean target strength as the dominance of hickory shad gave way to larger-sized striped bass. Though changes through time of target strength have been observed in concert with changes in fish size in other systems (Johnston and Hopelain 1990; Romakkaniemi et al. 2000), we conclude that the reflective qualities and behavior of fish targets are not distinguishable for the two most abundant species in this system. Additionally, the mean target strength measurements for four typically-sized American shad suspended in a frame fell between the 25th and 75th percentiles for all target strengths measured in both years.

Other acoustic variables not analyzed in this study may be more useful for species identification. Burwen et al. (2003) found that time-based signal characteristics (e.g., pulse width of returning echoes) were a better predictor of fish size than was target strength. Those signal characteristics may vary among species due to differences in swimming behavior, and appear promising for species identification in Alaskan rivers dominated by two species. The approach may be less practical in a southeastern river, given the high diversity of species in the mid-channel habitat. Hewitt (2003) recorded 39 species of fish in 2000-2002 sampling on the Roanoke River using a fishwheel, which sampled various portions of river channel. Nevertheless, it should be noted that target species dominated (> 80%) spring catches in this study, so further work on time-based signals for hickory shad, American shad, and striped bass is warranted.

Characterizing migratory behavior

A key question in estimating run size is the cross-channel distribution of upstream migrants. Our default estimates are based on the assumption that the density of fish in the unsampled section is the same as within the monitored 29.5-m wide section. Our estimates would be too low if high river flows caused fish to shift in distribution and migrate closer to the river banks. We cannot address this question using hydroacoustics but we note that mid-channel catches using drift gillnetting and electrofishing were low at flows greater than $283.2 \text{ m}^3 \text{ s}^{-1}$ ($10,000 \text{ ft}^3 \text{ s}^{-1}$). This is obviously not conclusive because both methods tend to be less effective when depths and flows increase.

There was no strong diurnal pattern to migration, based on hydroacoustic and species composition sampling. This has implications for statistical analyses and future sampling design. In 2004, catches of hickory shad and striped bass were not different across six periods of the day, though the result could be affected by day/night differences in effectiveness of drift gill nets. Mean hydroacoustic counts (which would include all species) were similar but significantly different by 8-hour blocks, with a slightly lower mean fish passage recorded between 00:00 and 08:00. There was no difference between the periods 08:00-16:00 and 16:00-24:00. The hydroacoustic counts would be heavily weighted towards hickory shad and striped bass because of their numerical dominance. Monitoring programs on the Delaware River document high American shad passage during two daytime periods (PACE 2001, 2003), though no statistical procedures are reported. Legget (2004) used telemetry to document peaks at dawn and dusk in American shad swimming speed on the Connecticut River.

Results based on species composition and hydroacoustic monitoring establish that target species collectively migrate upstream near the river bottom. We have more confidence in the gill-net results, as hydroacoustic results at short ranges are subject to a numerical bias caused by the beam geometry (which does not sample the complete vertical water column at near ranges). Previous hydroacoustic studies have shown that anadromous fishes often migrate close to the bottom (Daum and Osborne 1998, Ransom et al. 1998; Romakkaniemi et al. 2000; Hewitt 2003). Hewitt's results from a site 40 rkm downstream of the current site are particularly relevant. He determined that upstream-migrating striped bass were highly aggregated within 1.5 m of the bottom. A somewhat different result was reported for American shad in the Connecticut River (Witherell and Kynard 1990). At sites deeper than 7 m, they found that 83% of upstream and downstream migrating American shad were in the lower half of the water column. They add, however, that most fish were swimming more than 2 m off the river bottom.

Hydroacoustic sampling also provides strong evidence that upstream migrants (all species combined) are not homogeneously distributed across the river channel, but more associated with ranges near shore. Plots of range and elevation for individual fish tracks certainly make a case for spatial aggregation. Most fish tracks were detected in the first 15 m from the transducer. Again, this result is commonly seen in salmon studies, as the fish tend to migrate along the banks to avoid higher water velocities (Daum and Osborne 1998, Ransom et al. 1998). Our counts of upstream migrants at ranges greater than 15 m could possibly be biased because of the increased noise at long ranges. One approach for confirming our spatial pattern would be to supplement the fixed-aspect monitoring with a downward-looking

mobile survey. Chen et al. (2004) used this approach in the Frazier River, British Columbia, to verify the high density of salmon near shore.

Differences in cross-channel distribution between target species would not be apparent from the hydroacoustic data. Those results will predominately reflect striped bass because of their numerical dominance in May. Species composition results in this study confirm that American shad utilize the mid-channel habitat, but they were also collected in the shoreline transects. Legget (2004) reported that American shad adhere to the river channel during migrations in the Connecticut River, with only periodic movements into shallower water.

What it would take to have a really good estimate

The most common approach for sampling the cross-channel distribution is to position one or more transducers on each shoreline, so that the insonified zones cover most or all of the channel cross section (Daum and Osborne 1998, Ransom et al. 1998; Romakkaniemi et al. 2000; Burwen et al. 2003). This approach works particularly well in cases where flows and depths are high in the center of the channel, so that few fish would be found in any area not covered by the transducers. Care must be taken not to count the same fish twice, but this should be possible by adjusting the range covered by each transducer. Weirs are typically used along the shoreline to force fish to migrate further offshore, where they pass through a transducer beam.

The beam should be aimed as close as possible to the river bottom. The river bottom should slope away from the transducer, such that the expanding beam minimizes its contact with both the sediment and surface boundary layers. To produce accurate estimates using

only tracked fish, the signal-to noise ratio must be high and the fish density must be moderate to low (Mulligan and Kieser 1996, Kieser et al. 2005).

Species composition sampling is important to consider. Practical limitations to species composition sampling were encountered in 2004 and 2005. Sampling was only done on a subset of days, the effectiveness of both methods depended on river discharge, and the methods had different selectivity patterns in terms of the sizes and species captured and effectiveness at different depths. The number of fish captured was low on some days, resulting in poor estimates of species composition.

Accuracy of estimates

Accuracy of a hydroacoustic estimate can sometimes be evaluated through comparisons with an alternative approach. For example, Holmes et al. (2006) compared acoustic counts to visual counts of unrestrained migrating salmon and salmon constrained to pass through an enumeration fence. Johnston and Hopelain (1990) compared acoustic counts (fish per minute) to catch per haul seine. Visual counts are not an option for the Roanoke or other southeastern rivers, due to the low visibility. Correlative approaches, as used by Johnston and Hopelain (1990), provide some support for the hydroacoustic results but are less conclusive than comparing estimates of absolute run size. The correlation observed in this study between daily run size estimates and electrofishing CPUE is nevertheless encouraging.

It is important to examine the assumptions made in estimating run size. For example, we assume that a negligible proportion of Roanoke River resident species utilize the mid-channel habitat, so that species composition estimates can be based only on the three target species. Supporting that assumption is the observation that upstream passage is close to zero

at times in between pulses of anadromous fish. For example, estimates of upstream migrants are close to zero in mid to late April of both years. Additionally, resident species captured often in bank electrofishing are uncommon or absent in mid-channel sampling by both gears. Our run size estimates are also likely biased low because we did not extrapolate our run size estimates to days after 31 May, 2004 and 3 June, 2005. This was likely a greater bias in 2005, as daily estimates were still relatively high on most days near the end of the field season.

We have also ignored the possibility of point-source violations for our circular transducer. Dawson et al. (2000) remind investigators that split-beam tracking relies on accurately measuring the direction of movement for each fish track. This measurement is confounded at ranges close to the transducer (near-field), especially in cases where fish are highly reflective and the target is very large in relation to the beam's cross-sectional area. If we incorrectly measured direction of travel in the near-field, the bias could be significant at ranges < 2 m because the expansion factor from the beam height to river depth is very large.

For the default run size model (R_0), we assume there are no errors in hydroacoustic measurement or post-processing which would cause the likelihood of fish track detection to vary with range. The validity of this assumption is not known, but it is clear that fewer fish tracks were detected near the river bottom boundary layer at ranges greater than 15 m. The possibility that fish tracks are less detectable near the river bottom at distant ranges became the rationale for range truncations in models $R_1 - R_2$. Conversely, this may simply reflect the cross-channel distribution rather than missed detections, as was assumed in alternate run size estimates R_3 and R_4 . The assumption should be investigated further by methods independent of hydroacoustic sampling.

Alternate run size estimates show the importance of assumptions in regard to hydroacoustic detection and migratory behavior. Though all American shad model estimates were within an order of magnitude, striped bass estimates ranged from 95,000 to over 500,000 individuals, due primarily to the addition of date- and bank-specific information from electrofishing catches. Model R_2 was most restrictive in its assumptions, truncating accurate detections at 15 m range and preventing fish detected near the bottom from being extrapolated to the full river depth on any sample day. This estimate is acknowledged to be biased low because fish close to the transducer and in the >1 m vertical stratum pass undetected (refer to Figure 18). Nevertheless, this model is thought to be biologically realistic, based on the high density of acoustic targets near the bottom and the independent supporting evidence from 2005 gill netting.

It is also interesting that models R_0 and R_3 produce similar estimates. The null model's broad assumptions of uniform cross-channel density, along with complete vertical expansion, stand in contrast to model R_3 , which treats each bank and the channel as separate units. That the estimates are similar provides mild evidence that the nearness of acoustic targets to shore may reflect reality for the unsampled north bank, and that the mid-channel habitat could indeed be less utilized than habitat near the river banks.

There are few recent studies to compare against our estimates of American shad population size in the Roanoke River. Our default run size estimates for 2004-2005 (7-9 thousand individuals) are roughly similar (within an order of magnitude) to crude mark-recapture estimates carried out at Roanoke Rapids, NC in 1998 and 2001 (Bob Graham, personal communication). Historical population size would have been dramatically larger. The 1880 pound net harvest of American shad in Albemarle Sound, which would have

included an unknown percentage of fish returning to the Roanoke River, was 920,360 fish (Cobb 1906). The 1896 Albemarle Sound harvest was 735,000 fish, and the Roanoke River harvest was 169,000 fish (Stevenson 1899). Smith (1907) indicated that the peak of the American shad fishery in North Carolina was reached in 1896-1897. By 1904, the American shad catch had declined to 179,000 in Albemarle Sound and 15,000 in the Roanoke River (Cobb 1906).

Our striped bass estimates for 2004 and 2005 are low compared to other historic and modern population estimates (NCDMF and NCWRC 2004). Estimates in the latest stock assessment are based on Virtual Population Analyses (VPA), a technique for summing the catches by year class and adjusting upwards to account for natural mortality (NCDMF and NCWRC 2004). Although VPA estimates are least accurate in the most recent time steps (Hilborn and Walters 1992), the estimates of age 3+ spawners in the Albemarle-Roanoke stock have stabilized in recent years at about 1.2 million individuals. A very large but unknown proportion of those fish is thought to contribute to the Roanoke River migration, with the remainder spawning in other rivers in the watershed. Combining tag-recapture data from 1956 to 1983 (Hassler and Taylor 1984, reported in NCDMF and NCWRC 2004) and the current VPA results, only years between 1980 and the early 1990s result in estimates similar in magnitude to our null model striped bass estimates. The striped bass population is thought to have been at a critically low abundance during that period, following recruitment failure in the late 1970s, and was not declared a recovered stock until 1997. Model R₄, highest among alternative run size estimates, is still less than half of the recent VPA projections.

It is worth considering how many upstream migrants should be detected if, for illustration, 750,000 adult striped bass return to the spawning grounds near Weldon, NC. If we simply divide the hypothetical run size by 60 days, the expected value is 12,500 fish per day. In comparison, our null model estimates were less than half that number on every day in the 2005 season. According to model R₄, less than 50% of the daily estimates are greater than 12,500, with a peak migration less than 30,000 per day. The largest unknown is the spatial sampling fraction. If a majority of target species passed our study site on the northern bank, our estimates would be biased low by an unknown amount. Romakkaniemi et al. (2000) produced run size estimates for Atlantic salmon that were considered low, in that they merely matched the estimated harvest within the study period. They found decent agreement between hydroacoustic counts and independent indices of run timing, but suggested that the low estimates were due to incomplete cross-sectional spatial coverage. They covered 40-50% of the cross-section by deploying a transducer on each bank, but could not sample the mid-channel.

Precision of estimates

The methods of Skalski et al. (1993) provided variance estimators for a case where fish were counted passing through a rectangular opening (turbine intake). Their beam covered the entire range but only part of the width (because of the beam shape versus the rectangular turbine intake). In applying their method to our work, we inherit their assumption that the unsampled part of the turbine intake has the same average density as the sampled cross-sectional area. In our case, the assumption appears to be violated by the aggregation of fish tracks near the river bottom. There is also potential bias due to expanding from the sampled part of the river cross section (29.5 m) to the entire river width (80 m),

unless the densities were the same in the sampled and unsampled sections. This seems unlikely but is possible if fish are aggregated in a similar fashion on both sides of the river, as is assumed by alternate run size models R_3 and R_4

Spatial replication is difficult to consider for hydroacoustic studies due to the nature of a stationary transducer. For fixed-aspect acoustic studies, an investigator is likely restricted to the range and depth profile chosen when the gear is deployed (i.e., there is no probability that another cross-section may be sampled). The approach of expanding for an unsampled part of the channel is routine in riverine hydroacoustics (e.g., Johnston and Hopelain 1990; Romakkaniemi et al. 2000). It was thought to be acceptable for the Roanoke River, based on previous work showing that striped bass were uniformly distributed across the river channel (Hewitt 2003). However, the 2004-2005 results suggest that extrapolating counts to an unsampled portion of river cross-section may not be valid. Unless an additional transducer or mobile system becomes available, the next best option for future years may be to locate a sample site that is a better fit to the acoustic beam, so that more of the channel cross-section can be covered. That could also allow for a measure of spatial variability by generating estimates for individual range bins across the monitored portion of the river channel.

In 2005, the coefficients of variation ($SE / estimate \times 100$) for estimated run size were less than 10% for American shad and striped bass for all run size estimate models. That level of precision appears unlikely. Precision estimates do not take into account the unknown difference in density between any sampled and unsampled parts of the channel. Additionally, variance equations do not take into account the positive covariance among days in species proportions (due to the use of a seven-day moving average). The covariance

structure is complicated because species composition samples were not collected at even intervals of days.

Resource management implications

Our evidence suggests that all three target species actively migrated during daytime. There were no diurnal differences in catch of hickory shad and striped bass in species composition samples, and hydroacoustic counts were similar for the three 8-hour periods. This suggests that daytime species composition sampling will be adequate for the three target species, which benefits the visual nature of electrofishing.

It may be possible, once the technique is fully validated, to manage Roanoke River fisheries for anadromous species in real time. Hydroacoustic data are used in real-time management in a number of Alaskan rivers (e.g., Anchor, Kenai). These monitoring programs document that salmon escapement goals have been met before various harvest seasons are opened or closed (ADF&G Fish Count Data 2006). A similar approach could be useful in the Roanoke River, given the variability in spring flows and temperatures. Flow is an important determinant of striped bass recruitment success (Hassler et al. 1981, Rulifson and Manooch 1990), and water temperature indicates the initiation of spawning (Rulifson 1990, Carmichael 1998). In most years, the recreational fishery closes on 30 April. This static date is based on a historic pattern of peak spawning during the month of May (Hassler et al. 1981). However, should migrations arrive “early” due to a warmer than normal spring, or high quality spawning periods come “late” due to river conditions, the closure date may not meet the general management objective. Hydroacoustic monitoring could provide additional, fishery-independent information to aid management decisions.

In 2005, regional fishery managers extended the Roanoke River striped bass harvest season from 30 April to 5 May. The decision was based on April river flows, progression of water temperature, public comment, and relative catch data from the creel sampling survey (Pete Kornegay, personal communication). According to this study, on 5 May striped bass migration was just beginning a steady increase which did not peak until 23 May. As harvest is purposefully directed at the early portion of the run, additional open days may have been justified. In contrast, if warm weather initiated peak spawning period previous to 30 April, a decision to shorten the harvest season could be made with more confidence.

Future research

Better information is needed about how upstream-migrating fish respond to changes in flow. If upstream migration is actually unimpeded at high flows, but fish migrate outside of the detectable portion of river channel, then our daily estimates are biased low. Maximizing cross-sectional spatial coverage by installing transducers on each bank would increase equipment costs and post-processing, but would greatly reduce the uncertainty associated with our estimates. Additionally, a negatively sloped river bottom (depth increasing steadily with range) would also improve the fit of a conical circular sonar beam within the river cross-section. Transducers installed in approximately one meter of water depth would be easier to monitor and adjust, and shallow depths near each transducer would aid the installation of structures (fish weirs) to guide fish offshore and into the acoustic beam. If a site with a gradually sloping river bottom is not located, better cross-channel coverage could be achieved by purchasing elliptical transducers. These transducers provide a low, wide beam that can cover a greater range than a standard circular transducer. These

suggestions are considered ideal for hydroacoustic gear deployment (Enzenhofer and Cronkite 2000), but were not possible for the two years of this study.

Independent verification of channel use by target species would also benefit future research, notably techniques which can randomly sample spatial distribution within the entire river width. Drift gillnetting and electrofishing verify the presence and dominance of anadromous species in the mid-channel; however accurate measurement of a specimen's distance from shore is not possible. Another approach for examining the cross-channel distribution is to carry out a mobile survey, using a downward-looking transducer, in the part of the channel cross section that is not covered by the fixed-location transducer (Xie et al. 2002).

An additional option for characterizing migratory behavior and validating split-beam hydroacoustic results is to collect supplemental data using a dual frequency identification sonar system (DIDSON). This high-frequency system uses multiple near-simultaneous sound pulses at a frequency of 1.1-1.8 MHz to produce acoustic "images" that are captured as video files (Sound Metrics Corporation 2006). The approach can provide near-video quality images and sampling is effective during day or night and in turbid waters (Sound Metrics Corporation 2006). DIDSON technology has recently aided the study of salmon behavior near dams (Moursund et al. 2003) and has been recommended for monitoring salmon migrations in the Frazier River watershed (Holmes et al. 2005). The technology has also been shown to equal the precision of visual counts performed by human observers (Holmes et al. 2006). In contrast to split-beam data, generic fish targets (e.g., small fish, big fish, drifting debris) can be visually identified and total lengths can be estimated within processing software. At highest resolution, the maximum sampling range for the DIDSON

system (15 m) is less than the horizontal range of traditional hydroacoustics. It could, however, be a valuable tool for studying the cross-channel distribution, particularly by application in downward-looking orientation from a mobile or anchored vessel. The video files would also be valuable to examining migratory behavior and for validating the split-beam counts.

CONCLUSIONS

The results of this study suggest that hydroacoustic monitoring is a promising approach for estimating the run size of American shad and striped bass in the Roanoke River, NC. Tracks of upstream-migrating fish are readily discernable from ambient (random) acoustic noise, and a single set of fish tracking parameters was sufficient for post-processing all files from both field seasons. The largest uncertainty regarding the hydroacoustic monitoring is the cross-channel distribution of upstream migrants. The hydroacoustic beam covers only about one-third of the channel cross-section, because of the water depth at the study site and the transducer's effective beam angle. Temporal coverage is limited by the time required for post-processing of samples. Analysis methods were standardized in 2005 based on lessons learned in 2004, and successfully incorporate a two-way (i.e., day, 8-hr period) stratified random sampling design. Traditional fisheries sampling appears to provide an adequate measure of the seasonal presence and absence of target species. Using a seven-day moving average smooths the day-to-day variability in species composition estimates, and makes it possible to generate daily estimates from five days per week of sampling.

Our study points to the difficulty in assessing the abundance of a target species that is rare in biological samples. American shad were the main target species in this study but made up only about 2% of the combined 2005 electrofishing catch for the three target species. Their relatively low abundance makes it critical to use a method where the largest possible sample size can be obtained, and where a more abundant species (i.e., striped bass) can be released unharmed after processing. For those reasons, we recommend daytime electrofishing as the primary sampling gear. Comparative studies using other gears should be continued, in order to better understand how changes in water depth and flow affect within-

day estimates of species proportions. Another study focus should be to determine whether supplemental sampling with a passive gear, such as a drift gill net, can provide directional movement information. Currently, it is not known to what degree downstream-migrating fish affect the electrofishing estimates of species proportions.

This project has produced a great deal of site-specific information which should aid the study of anadromous migrations in the Roanoke River. The target species support economically and culturally important fisheries, and affect the operation of upstream hydroelectric dams. In addition, considerable public resources are invested in monitoring and restoring these populations. For these reasons, it is essential to validate the hydroacoustic estimates and to make the estimates as accurate and precise as possible. Further research to address the questions outlined above will allow fishery managers to use the hydroacoustic results with confidence in making management decisions.

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Table 1. Total number of adult fish sampled by traditional fisheries methods for 2004. Efforts took place between 15 March and 28 May at the Halifax study site, and are summed by species and gear.

Common name	Species	Gill netting	Electrofishing	Electrofishing by river position			All gear total
		Total	Total	North Bank	Channel	South Bank	
Striped bass	<i>Morone saxatilis</i>	337	85	53	29	3	422
Hickory shad	<i>Alosa mediocris</i>	105	95	38	36	21	200
Blueback herring	<i>Alosa aestivalis</i>	22	16	13	1	2	38
Common carp	<i>Cyprinus carpio</i>	1	33	9	-	24	34
Shorthead redhorse	<i>Moxostoma macrolepidotum</i>	17	14	3	4	7	31
Longnose gar	<i>Lepisosteus osseus</i>	3	28	20	-	8	31
Channel catfish	<i>Ictalurus punctatus</i>	12	11	7	3	1	23
Gizzard shad	<i>Dorosoma cepedianum</i>	1	22	14	1	7	23
Largemouth bass	<i>Micropterus salmoides</i>	-	20	7	-	13	20
White catfish	<i>Ameiurus catus</i>	11	3	1	-	2	14
Redbreast sunfish	<i>Lepomis auritus</i>	-	13	1	-	12	13
American shad	<i>Alosa sapidissima</i>	5	4	-	1	3	9
White perch	<i>Morone americana</i>	2	7	5	1	1	9
Notchlip redhorse	<i>Moxostoma collapsum</i>	-	9	5	-	4	9
Bluegill	<i>Lepomis macrochirus</i>	-	7	3	-	4	7
Bowfin	<i>Amia calva</i>	-	7	5	-	2	7
Redear sunfish	<i>Lepomis microlophus</i>	-	6	4	-	2	6
Yellow perch	<i>Perca flavescens</i>	-	5	-	-	5	5
Blue catfish	<i>Ictalurus furcatus</i>	1	1	-	-	1	2
American Eel	<i>Anguilla rostrata</i>	-	2	1	-	1	2
Striped mullet	<i>Mugil cephalus</i>	-	2	2	-	-	2
Moxostoma sp.	<i>Moxostoma sp.</i>	1	-	-	-	-	1
Flat bullhead	<i>Ameiurus platycephalus</i>	-	1	1	-	-	1
Southern flounder	<i>Paralichthys lethostigma</i>	-	1	-	-	1	1
		518	392				910

Table 2. Total number of adult fish sampled by traditional fisheries methods for 2005. Efforts took place between 04 March and 04 June at the Halifax study site, and are summed by species and gear.

Common name	Species	Gill netting	Electrofishing	Electrofishing by river position			All gear total
		Total	Total	North Bank	Channel	South Bank	
Striped bass	<i>Morone saxatilis</i>	153	841	622	115	104	994
Hickory shad	<i>Alosa mediocris</i>	12	749	379	27	343	761
Notchlip redhorse	<i>Moxostoma collapsum</i>	3	187	121	7	59	190
Gizzard shad	<i>Dorosoma cepedianum</i>	1	180	86	5	89	181
Common carp	<i>Cyprinus carpio</i>	1	126	54	2	70	127
Striped mullet	<i>Mugil cephalus</i>	-	116	28	1	87	116
Bowfin	<i>Amia calva</i>	-	96	63	1	32	96
Redbreast sunfish	<i>Lepomis auritus</i>	-	79	24	2	53	79
Largemouth bass	<i>Micropterus salmoides</i>	-	76	23	1	52	76
Longnose gar	<i>Lepisosteus osseus</i>	-	64	35	1	28	64
American shad	<i>Alosa sapidissima</i>	15	48	12	20	16	63
Shorthead redhorse	<i>Moxostoma macrolepidotum</i>	4	47	23	1	23	51
Channel catfish	<i>Ictalurus punctatus</i>	-	47	34	3	10	47
White perch	<i>Morone americana</i>	-	43	39	1	3	43
Blueback herring	<i>Alosa aestivalis</i>	-	42	10	9	23	42
Bluegill	<i>Lepomis macrochirus</i>	-	30	13	-	17	30
White catfish	<i>Ameiurus catus</i>	-	21	21	-	-	21
Yellow perch	<i>Perca flavescens</i>	-	16	9	-	7	16
Redear sunfish	<i>Lepomis microlophus</i>	-	5	3	-	2	5
Sea Lamprey	<i>Petromyzon marinus</i>	-	3	-	-	3	3
Chain Pickerel	<i>Esox niger</i>	-	3	1	-	2	3
American Eel	<i>Anguilla rostrata</i>	-	2	-	-	2	2
Black Crappie	<i>Pomoxis nigromaculatus</i>	-	1	-	-	1	1
Golden Shiner	<i>Notemigonus crysoleucas</i>	-	1	1	-	-	1
Blue catfish	<i>Ictalurus furcatus</i>	1	-	-	-	-	1
Flier	<i>Centrarchus macropterus</i>	-	1	-	-	1	1
Quillback	<i>Carpionodes cyprinus</i>	-	1	1	-	-	1
		190	2825				3015

Table 3. Gillnetting catch from two 100 m drifts by date, mesh size and species group for 2004. The field OTH is a sum of species other than American shad, hickory shad and striped bass. Equal efforts were made on all days, drifting each mesh size twice. The symbol . represents a catch of zero.

Date	7 mm				10 mm				14 mm			
	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH
15-Mar	6	.	.	.	.	.	1
17-Mar	6	.	.	.	.	.	.
19-Mar	7	.	.	.	.	.	.
21-Mar	.	1	.	7	.	15	1	.	.	.	.	.
23-Mar	.	.	.	2	.	8	.	2	.	.	.	.
25-Mar	.	1	.	2	.	2	.	.	.	.	.	.
27-Mar	.	1	.	3	.	2	.	.	.	.	.	.
29-Mar	.	4	1	3	.	8	.	1	.	.	.	.
31-Mar	.	7	.	9	.	15	.	2	1	1	.	.
2-Apr	1	.	.	.	.
4-Apr	.	.	.	3	.	1	.	.	.	.	.	.
6-Apr	.	1	.	2	.	8	1	.	.	.	.	.
8-Apr	.	.	.	3	.	1	.	.	.	.	.	.
10-Apr	.	1	.	7	.	1	3	.	.	.	1	1
12-Apr	.	.	.	4	1	4	1	1	.	.	.	.
15-Apr
16-Apr
18-Apr	.	2	.	.	.	1	.	.	.	.	.	.
20-Apr
22-Apr	.	.	.	2	.	.	.	.	.	.	.	.
24-Apr	.	1	.	.	.	.	2	.	.	.	.	.
26-Apr
28-Apr	.	.	.	1	.	.	.	3	.	.	.	1
30-Apr	.	.	.	2	.	.	1	.	.	.	1	.
2-May	.	.	2	1	1	.	2	.	.	.	.	.
4-May
6-May	1
8-May	2	.	11	.	.	.	1	.
10-May	.	.	26	.	.	.	23	2	.	.	1	.
12-May	.	.	2	.	.	.	53	1	.	.	3	.
14-May	.	.	2	.	.	.	45	1	.	.	.	1
16-May	.	.	7	.	.	.	42	.	.	.	1	.
18-May	.	.	9	.	.	.	43	1	.	.	2	.
20-May	.	.	5	.	.	.	8	.	.	.	.	.
22-May
24-May	1	.	.	.	.	.
26-May
28-May	1	.	.	.	.

Table 4. Gillnetting catch from two 200 m drifts by date, mesh size and species group for 2005. The field OTH is a sum of species other than American shad, hickory shad and striped bass. Equal efforts were made on all days, drifting each mesh size twice. The symbol . represents a catch of zero.

Date	7mm				10mm				14mm			
	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH
7-Mar	1
9-Mar
10-Mar
11-Mar
14-Mar
15-Mar	2	.	.	.	.	.	.
16-Mar
17-Mar	2	.	.	.	.	.	.
18-Mar
21-Mar
22-Mar
23-Mar
24-Mar
25-Mar
28-Mar	1	.	.	.	.	.	.
29-Mar	1	.	1	.	.	.	.
30-Mar
31-Mar
1-Apr
4-Apr	1	.	.	.	.	.	.
5-Apr
6-Apr
7-Apr
8-Apr
12-Apr	3	1	.	.	.	.	.
13-Apr	.	2	.	.	.	.	.	1	.	.	.	.
14-Apr
15-Apr
18-Apr
19-Apr
20-Apr
21-Apr	1	.	1	.	.	.	.	.
22-Apr	3	.	.	.	.	.
25-Apr
26-Apr
27-Apr
28-Apr
29-Apr	1	.
2-May	1	.	.	.	.
3-May	1	.	.	.	.
4-May	2	.	.	.	.
5-May	1	.	.	.	.	.	.	.
9-May	1	1	.	.	.

Table 4. --- continued.

Date	7mm				10mm				14mm			
	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH
10-May
11-May	1	.	.	.	.	.	.	.
12-May	.	.	2	.	.	.	13	.	.	.	1	1
13-May	.	.	1	.	2	.	6	.	.	.	.	.
16-May	5	.	.	.	.	.
17-May	2	.	1	.	.	.
18-May	1	.	3	1	.	.	.	1
19-May	.	.	5	.	.	.	3	.	.	.	.	.
20-May	2	.	9	.	.	.	.	.
23-May	1	.	3	.	3	.	9	.	.	.	.	.
24-May	.	.	5	.	.	.	43	.	.	.	.	.
25-May	.	.	3	.	1	.	8	.	.	.	1	.
26-May	1	.	.	.	.	.
27-May	.	.	6	.	.	.	.	.	.	.	1	.
30-May
31-May	.	.	8	.	.	.	7	.	.	.	.	.
4-Jun	.	.	2	.	.	.	.	.	.	.	.	.

Table 5. Distance from leadline for target species captured by gillnetting in 2005. Drift gill nets were marked in 1-m horizontal bands, and choice of net depth was adjusted to sample the entire water column (surface to river bottom).

Distance from leadline (m)	# American shad	# hickory shad	# striped bass	# all target species
0 - 1	7	9	87	103
1 - 2	3	1	44	48
2 - 3	3	0	14	17
3 - 4	2	1	5	8
4 - 5	0	1	0	1
5 - 6	0	0	0	0

Table 6. Electrofishing catches by date, transect location and species group for 2004. The field OTH is a sum of species other than American shad, striped bass and hickory shad. There was a double sample on 29 April. The symbol . represents catch of zero.

Date	North Bank				Channel				South Bank			
	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH
11-Mar	.	1	.	13	.	12	.	3	.	3	.	13
18-Mar	.	14	.	17	.	.	.	.	.	16	.	6
1-Apr	.	2	.	27	.	23	.	6	.	.	.	21
15-Apr	.	12	.	8	.	1	.	.	.	2	.	8
29-Apr	.	.	16	10	.	.	13	1	.	.	3	10
29-Apr	.	.	22	9	.	.	2	.	1	.	.	10
12-May	.	.	15	11	1	.	14	.	.	.	.	18
26-May	.	.	.	6	.	.	.	.	2	.	.	11

Table 7. Electrofishing catches by date, transect location and species group for 2005. The field OTH is a sum of species other than American shad, striped bass and hickory shad. The symbol . represents catch of zero. Equal efforts were made on all days.

Date	North Bank				Channel				South Bank			
	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH
4-Mar	.	.	.	14	.	.	.	.	.	2	.	.
7-Mar	.	.	.	2	.	.	.	.	.	.	.	4
9-Mar	.	.	.	9	.	.	.	.	.	3	.	6
10-Mar	.	6	.	2	.	.	.	.	.	8	.	1
11-Mar	.	2	.	5	.	.	.	.	.	3	.	3
14-Mar	.	1	.	2	.	.	.	4	.	5	.	3
15-Mar	.	3	.	4	1	1	.	.	.	14	.	.
18-Mar	.	16	.	1	.	1	.	.	.	26	.	1
21-Mar	.	11	.	1	.	.	.	1	.	6	.	1
22-Mar	.	1	.	.	.	.	.	.	.	6	.	.
23-Mar	.	8	.	1	.	.	.	.	.	16	.	1
24-Mar	.	10	.	2	.	.	.	.	.	16	.	7
25-Mar	1	27	.	1	.	.	.	.	.	11	.	3
28-Mar	.	20	.	5	.	.	.	.	.	27	.	2
29-Mar	.	24	.	3	1	.	.	.	.	50	.	5
30-Mar	.	25	.	.	.	.	.	.	.	9	.	1
31-Mar	.	13	.	1	.	.	.	.	.	.	.	.
1-Apr	.	20	.	1	.	.	.	.	.	26	.	2
4-Apr	.	25	.	1	.	.	.	.	.	23	.	.
5-Apr	.	15	.	1	.	.	.	.	.	16	.	1
6-Apr	10	.	1
7-Apr	.	40	.	2	.	.	.	.	.	25	.	1
8-Apr	17	.	.	.	.	.	.
12-Apr	.	22	.	6	.	.	.	.	.	6	.	9
14-Apr	.	29	3	11	.	.	.	.	.	11	.	13
15-Apr	.	8	.	12	.	1	1	.	.	9	.	5
18-Apr	.	20	4	13	.	2	4	.	.	8	.	6
19-Apr	.	18	6	13	.	4	.	.	.	4	.	15
20-Apr	.	3	5	23	.	.	.	.	.	.	.	18
21-Apr	.	8	11	1	.	.	.	.	.	3	.	16
22-Apr	.	4	8	15	1	.	3	.	.	.	2	22
25-Apr	.	.	17	11	.	.	1	1	.	.	.	14
26-Apr	.	.	17	17	.	1	.	.	.	.	1	21
27-Apr	.	.	15	17	.	.	4	.	.	.	1	25
28-Apr	.	.	6	12	.	.	1	.	.	.	.	26
29-Apr	.	.	17	18	.	.	.	.	.	.	1	2
2-May	.	.	35	16	.	.	1	.	.	.	.	19
3-May	.	.	20	12	1	.	2	1	.	.	.	22
4-May	.	.	34	7	.	.	1	.	.	.	.	24
5-May	.	.	36	18	.	.	1	5	.	.	6	15
9-May	.	.	12	12	2	.	.	2	.	.	2	12
10-May	.	.	31	9	1	.	.	.	.	.	3	13
11-May	1	.	1	.	.	.	22	16	1	.	2	16
12-May	1	.	34	27	2	.	1	.	.	.	3	15

Table 7. --- continued.

Date	North Bank				Channel				South Bank			
	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH	ASH	HSH	STB	OTH
13-May	.	.	23	24	1	.	1	.	.	.	12	16
17-May	.	.	21	21	2	.	4	.	2	.	6	14
18-May	4	.	16	18	2	.	2	.	1	.	7	17
19-May	.	.	18	23	.	.	1	1	1	.	7	13
20-May	.	.	21	3	1	.	4	.	1	.	2	18
23-May	.	.	26	29	1	.	13	.	.	.	4	17
24-May	2	.	21	28	.	.	15	.	.	.	6	14
25-May	.	.	20	19	2	.	6	.	.	.	8	12
26-May	.	.	35	15	1	.	4	1	2	.	7	7
27-May	.	.	27	11	.	.	8	1	3	.	9	3
30-May	.	.	51	11	.	.	7	.	1	.	14	14
31-May	3	.	23	1	.	.	6	2	3	.	1	16
4-Jun	.	.	8	15	1	.	2	.	1	.	.	14

Table 8. Distance from river bottom for individual fish tracks in 2004 and 2005. Errors in estimated position result in a few fish being located below the river bottom during 2004 (7%). These positioning errors most often occur for fish close to the bottom (Don Degan, personal communication), and may also be due to transducer relocation following the 12 April to 16 April malfunction.

Distance from bottom (m)	# fish tracks 2004	# fish tracks 2005
-1 - 0	56	0
0 - 1	650	1420
1 - 2	83	399
2 - 3	19	174
3 - 4	0	98
4 - 5	0	18
5 - 6	0	8

Table 9. Hydroacoustic run size estimates by day for 2004. The estimated total migration from 3 April to 31 May was 284,289 individuals, totaling 9,046 American shad, 149,067 hickory shad and 126,176 striped bass. Linear interpolation was used to adjust for missed days due to gear malfunction (shaded rows).

Date	# Fish summed 0.5 - 30.0 m	α temporal fraction	α spatial fraction	Estimated Run (All spp)	ASH	HSH	STB
3-Apr	142.2	0.0139	0.3688	27773.7	505	26259	1010
4-Apr	161.8	0.0139	0.3688	31585.3	545	27773	3267
5-Apr	54.7	0.0139	0.3688	10683.4	184	9394	1105
6-Apr	38.1	0.0139	0.3688	7443.7	244	6345	854
7-Apr	94.3	0.0139	0.3688	18408.6	604	15693	2112
8-Apr	217.0	0.0556	0.3688	10591.7	415	8930	1246
9-Apr	96.1	0.0139	0.3688	18770.1	736	15826	2208
10-Apr	47.0	0.0139	0.3688	9179.3	306	6425	2448
11-Apr	49.0	0.0139	0.3688	9565.2	319	6696	2551
12-Apr	59.3	0.0139	0.3688	11577.1	373	7469	3735
13-Apr				6084.6	196	3926	1963
14-Apr				3338.3	108	2154	1077
15-Apr				1965.1	63	1268	634
16-Apr				1278.6	41	825	412
17-Apr	3.0	0.0139	0.3688	592.0	19	382	191
18-Apr	3.9	0.0139	0.3688	754.1	58	319	377
19-Apr	0.0	0.0139	0.3688	0.0	0	0	0
20-Apr	8.6	0.0556	0.3688	420.3	32	178	210
21-Apr	105.2	0.3333	0.3688	856.1	66	362	428
22-Apr	5.3	0.0139	0.3688	1027.4	79	435	514
23-Apr	2.7	0.0139	0.3688	519.3	40	220	260
24-Apr	0.0	0.0139	0.3688	0.0	0	0	0
25-Apr	65.4	0.0139	0.3688	12775.1	1455	3234	8086
26-Apr	105.0	0.0556	0.3688	5123.7	584	1297	3243
27-Apr	39.7	0.0139	0.3688	7760.3	884	1965	4912
28-Apr	9.8	0.0139	0.3688	1908.2	217	483	1208
29-Apr	1.0	0.0139	0.3688	196.8	22	50	125
30-Apr	1.1	0.0139	0.3688	216.9	12	21	184
1-May	57.7	0.0139	0.3688	11266.9	607	1079	9580
2-May	27.3	0.0556	0.3688	1330.6	30	35	1266
3-May	0.0	0.0139	0.3688	0.0	0	0	0
4-May	0.0	0.0139	0.3688	0.0	0	0	0
5-May	2.3	0.0139	0.3688	455.9	10	12	434
6-May	0.0	0.0139	0.3688	0.0	0	0	0
7-May	0.0	0.0139	0.3688	0.0	0	0	0
8-May	6.2	0.0139	0.3688	1206.8	20	6	1182
9-May	9.4	0.0139	0.3688	1843.2	30	9	1805
10-May	2.0	0.0139	0.3688	390.5	5	0	385
11-May	24.8	0.0139	0.3688	4851.7	65	0	4787
12-May	0.0	0.0139	0.3688	0.0	0	0	0
13-May	39.6	0.0139	0.3688	7732.3	86	0	7646
14-May	9.0	0.0139	0.3688	1750.9	14	0	1737
15-May	46.3	0.0139	0.3688	9036.6	70	0	8967

Table 9.--- continued.

Date	# Fish summed 0.5 - 30.0 m	α temporal fraction	α spatial fraction	Estimated Run (All spp)	ASH	HSB	STB
16-May	46.0	0.0139	0.3688	8982.2	0	0	8982
17-May	18.1	0.0139	0.3688	3539.7	0	0	3540
18-May	128.2	0.0139	0.3688	25026.1	0	0	25026
19-May	3.0	0.0139	0.3688	593.9	0	0	594
20-May	0.0	0.0139	0.3688	0.0	0	0	0
21-May	7.0	0.0139	0.3688	1360.1	0	0	1360
22-May	0.0	0.0139	0.3688	0.0	0	0	0
23-May	0.0	0.0139	0.3688	0.0	0	0	0
24-May	0.0	0.0139	0.3688	0.0	0	0	0
25-May	0.0	0.0139	0.3688	0.0	0	0	0
26-May	15.3	0.0556	0.3688	744.8	0	0	745
27-May	0.0	0.0139	0.3688	0.0	0	0	0
28-May	3.2	0.0139	0.3688	627.7	0	0	628
29-May	0.0	0.0139	0.3688	0.0	0	0	0
30-May	16.2	0.0139	0.3688	3154.6	0	0	3155
31-May	0.0	0.0139	0.3688	0.0	0	0	0

Table 10. Hydroacoustic run size estimate by day for 2005. The estimated total migration from 9 March to 3 June was 156,098 individuals ($\pm 6,101$ SE), totaling 7,054 American shad, 30,266 hickory shad and 118,778 striped bass. Linear interpolation was used to adjust for missed days due to gear malfunction (shaded rows).

Date	# Fish summed 0.5 - 30.0 m	α temporal fraction	α spatial fraction	Estimated Run (All spp)	SE	ASH	HSH	STB
9-Mar	1.6	0.1250	0.3688	34	31.6	1	33	0
10-Mar	7.3	0.1250	0.3688	157	92.6	3	154	0
11-Mar	3.6	0.1250	0.3688	79	73.8	1	78	0
12-Mar	14.8	0.1250	0.3688	320	77.3	4	317	0
13-Mar	3.8	0.1250	0.3688	83	54.6	1	82	0
14-Mar	13.0	0.1250	0.3688	282	120.1	3	280	0
15-Mar	3.0	0.1250	0.3688	65	45.5	1	65	0
16-Mar	13.0	0.1250	0.3688	283	198.2	3	280	0
17-Mar	4.6	0.1250	0.3688	100	66.0	1	99	0
18-Mar	7.2	0.1250	0.3688	157	77.3	1	155	0
19-Mar	54.2	0.1250	0.3688	1176	590.5	11	1165	0
20-Mar	59.5	0.1250	0.3688	1292	438.6	12	1280	0
21-Mar	38.8	0.1250	0.3688	843	473.0	6	837	0
22-Mar	7.8	0.1250	0.3688	170	158.6	2	168	0
23-Mar	3.4	0.1250	0.3688	73	49.1	0	73	0
24-Mar	25.9	0.1250	0.3688	563	99.6	5	558	0
25-Mar	61.4	0.1250	0.3688	1332	373.2	11	1321	0
26-Mar	134.7	0.1250	0.3688	2922	501.9	22	2900	0
27-Mar	11.8	0.1250	0.3688	255	118.5	2	254	0
28-Mar	52.4	0.1250	0.3688	1137	977.0	9	1128	0
29-Mar	40.8	0.1250	0.3688	884	493.6	6	878	0
30-Mar	0.0	0.1250	0.3688	0	0.0	0	0	0
31-Mar	7.3	0.1250	0.3688	158	147.6	1	157	0
1-Apr	16.1	0.1250	0.3688	350	167.8	1	349	0
2-Apr	46.0	0.1250	0.3688	999	453.8	4	995	0
3-Apr	17.7	0.1250	0.3688	384	194.5	1	383	0
4-Apr	12.8	0.1250	0.3688	277	196.1	0	277	0
5-Apr	7.6	0.1250	0.3688	165	110.0	0	165	0
6-Apr	31.3	0.1250	0.3688	680	582.1	0	680	0
7-Apr	5.0	0.1250	0.3688	108	101.5	0	107	1
8-Apr	4.2	0.1250	0.3688	92	61.5	0	90	2
9-Apr	40.9	0.1250	0.3688	887	672.7	0	870	17
10-Apr	87.9	0.1250	0.3688	1907	1726.3	0	1871	36
11-Apr				1349	875.2	0	1323	25
12-Apr	36.4	0.1250	0.3688	790	289.6	0	747	43
13-Apr	30.1	0.1250	0.3688	652	405.0	0	616	36
14-Apr	34.7	0.1250	0.3688	752	531.4	0	696	56
15-Apr	34.0	0.1250	0.3688	738	227.9	0	646	92
16-Apr				468	122.8	0	410	58
17-Apr	9.1	0.1250	0.3688	198	91.3	0	174	25
18-Apr	50.5	0.1250	0.3688	1097	637.1	0	900	196
19-Apr	25.4	0.1250	0.3688	550	179.2	3	403	144

Table 10.--- continued.

Date	# Fish summed 0.5 - 30.0 m	α temporal fraction	α spatial fraction	Estimated Run (All spp)	SE	ASH	HSH	STB
20-Apr	112.0	0.1250	0.3688	2430	1055.2	16	1442	972
21-Apr	138.1	0.1250	0.3688	2995	648.3	19	1449	1527
22-Apr	172.5	0.1250	0.3688	3743	1323.5	27	1229	2486
23-Apr	124.8	0.1250	0.3688	2708	740.7	20	889	1799
24-Apr	60.6	0.1250	0.3688	1314	523.7	10	432	873
25-Apr	125.8	0.1250	0.3688	2730	919.8	24	463	2243
26-Apr	105.9	0.1250	0.3688	2298	687.3	19	301	1977
27-Apr	100.1	0.1250	0.3688	2171	748.3	16	80	2076
28-Apr	17.7	0.1250	0.3688	384	161.4	3	3	379
29-Apr	26.2	0.1250	0.3688	568	188.0	4	4	560
30-Apr				357	209.7	2	2	352
1-May				919	232.1	6	6	908
2-May	48.1	0.1250	0.3688	1043	375.0	6	0	1038
3-May	79.4	0.1250	0.3688	1722	485.9	29	0	1693
4-May	81.6	0.1250	0.3688	1770	385.0	34	0	1735
5-May	23.8	0.1250	0.3688	515	149.3	14	0	501
6-May				886	311.7	25	0	862
7-May				1758	340.4	49	0	1709
8-May	108.3	0.1250	0.3688	2349	605.3	66	0	2284
9-May	108.9	0.1250	0.3688	2362	931.6	97	0	2266
10-May	161.0	0.1250	0.3688	3492	821.0	134	0	3358
11-May	78.8	0.1250	0.3688	1709	672.7	95	0	1614
12-May	90.2	0.1250	0.3688	1958	668.7	176	0	1782
13-May	96.6	0.1250	0.3688	2096	467.0	170	0	1925
14-May	147.2	0.1250	0.3688	3194	1013.1	259	0	2935
15-May	187.9	0.1250	0.3688	4077	1140.9	331	0	3746
16-May	142.8	0.1250	0.3688	3097	353.8	251	0	2846
17-May	197.9	0.1250	0.3688	4294	1191.1	377	0	3918
18-May	192.4	0.1250	0.3688	4174	629.9	324	0	3850
19-May	124.5	0.1250	0.3688	2700	521.6	196	0	2504
20-May	130.4	0.1250	0.3688	2828	564.7	218	0	2611
21-May	164.0	0.1250	0.3688	3558	1060.9	274	0	3284
22-May	164.1	0.1250	0.3688	3561	736.4	274	0	3287
23-May	306.0	0.1250	0.3688	6639	1141.5	458	0	6181
24-May	189.4	0.1250	0.3688	4109	1148.8	208	0	3901
25-May	284.7	0.1250	0.3688	6177	668.3	269	0	5909
26-May	125.4	0.1250	0.3688	2721	496.4	149	0	2572
27-May	224.6	0.1250	0.3688	4872	1266.3	312	0	4561
28-May	240.5	0.1250	0.3688	5217	1489.8	334	0	4883
29-May	228.0	0.1250	0.3688	4947	546.1	317	0	4631
30-May	233.5	0.1250	0.3688	5067	921.8	324	0	4743
31-May	228.3	0.1250	0.3688	4953	808.8	317	0	4637
1-Jun	167.7	0.1250	0.3688	3638	1090.7	233	0	3405
2-Jun	67.8	0.1250	0.3688	1471	369.0	94	0	1377
3-Jun	263.6	0.1250	0.3688	5718	1439.9	366	0	5352

Table 11. Alternate run size and standard error estimates. A variance estimator for model R₄ has not been developed.

Run size model	Total estimate	# American shad	# hickory shad	# striped bass	SE American shad	SE hickory shad	SE striped bass
R ₀	156,098	7,054	30,266	118,778	449.9	2,981.1	4,799.0
R ₁	298,223	13,604	55,338	229,281	887.0	11,450.6	17,506.6
R ₂	126,662	5,422	26,711	94,529	346.4	1,743.7	3,807.0
R ₃	165,455	7,485	31,917	126,053	582.9	2,225.1	7,269.2
R ₄	585,651	6,940	43,961	534,750	-	-	-

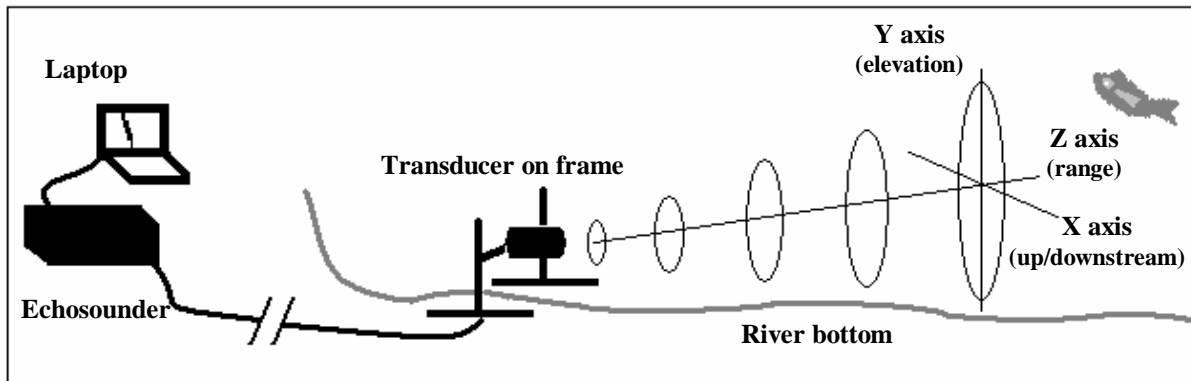


Figure 1. Top panel: Transducer frame, transducer, cable and rotation motor. Bottom panel: Schematic of hydroacoustic system transmitting from the river bottom.

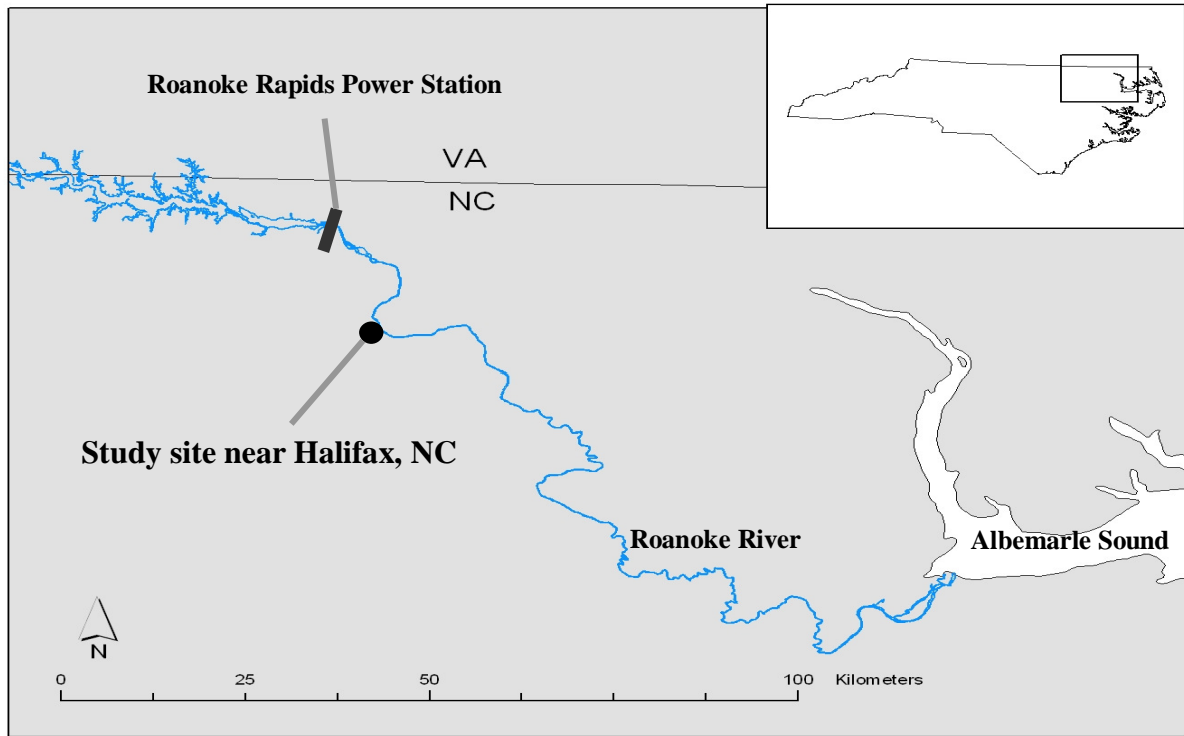


Figure 2. Hydroacoustic monitoring site near Halifax, North Carolina, used in 2004 and 2005, distant view.

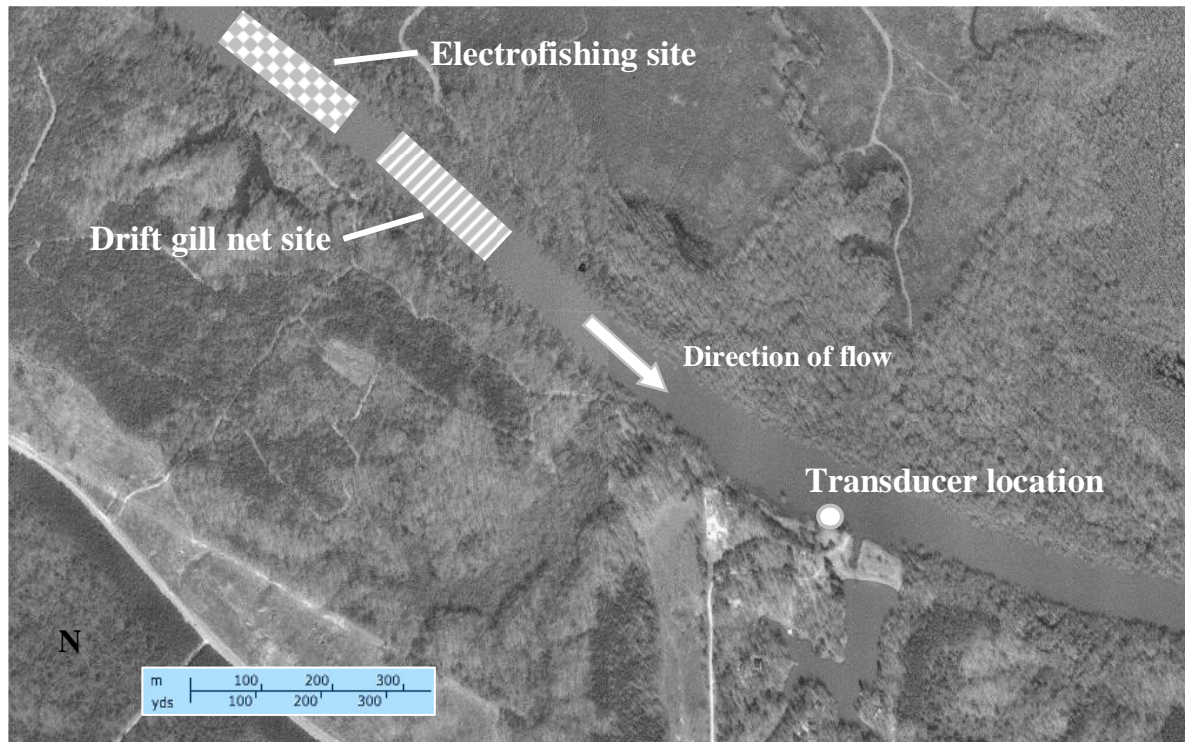


Figure 3. Area of study in 2004 and 2005, local view. The transducer frame was located approximately 6 meters from the south bank of the Roanoke River in 2004 and 2005, 2.4 km downstream of Halifax, NC. It was directed across the river, perpendicular to the flow of current.

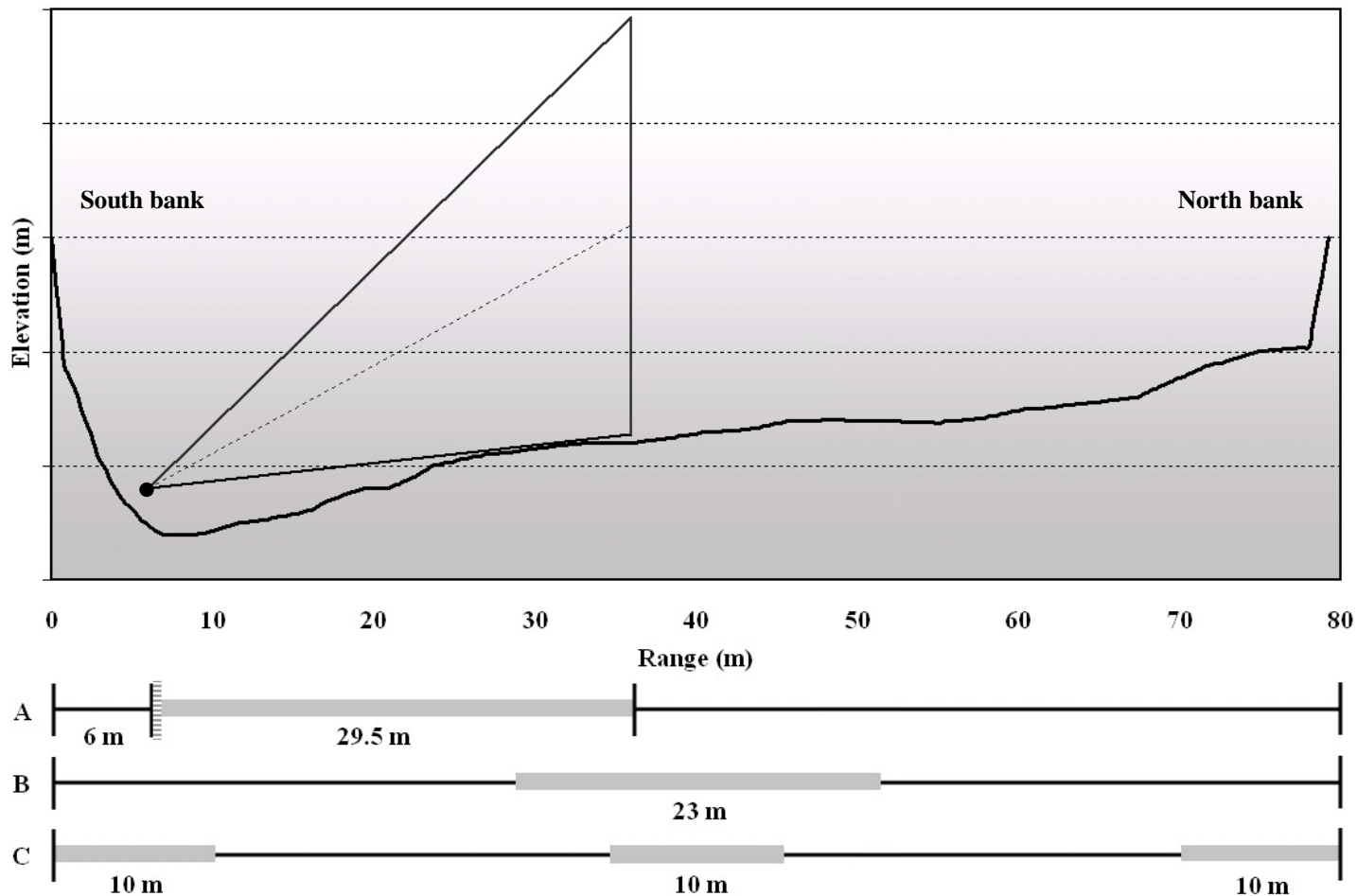


Figure 4: Bathymetry of the Roanoke River at the study site, plan view, with illustrated sampling fractions. Bottom profile data were collected on 30 March, 2004 using the project echosounder in a downward-looking orientation. A transducer with 7° nominal beam angle is represented, with the apex located at the approximate transducer location in both years (6 m from south bank, 2.2 m below water surface on 3 April, 2004). Theoretical linear projections of hydroacoustic sampling fraction (A), width of gill nets (B), and bank and channel electrofishing (C) are displayed to scale. Hydroacoustic detections within 0.5 m of the transducer were not considered (barred region of line A). Gill-net sampling extended from water surface to river bottom. A 10-m horizontal range of influence for electrofishing is assumed.

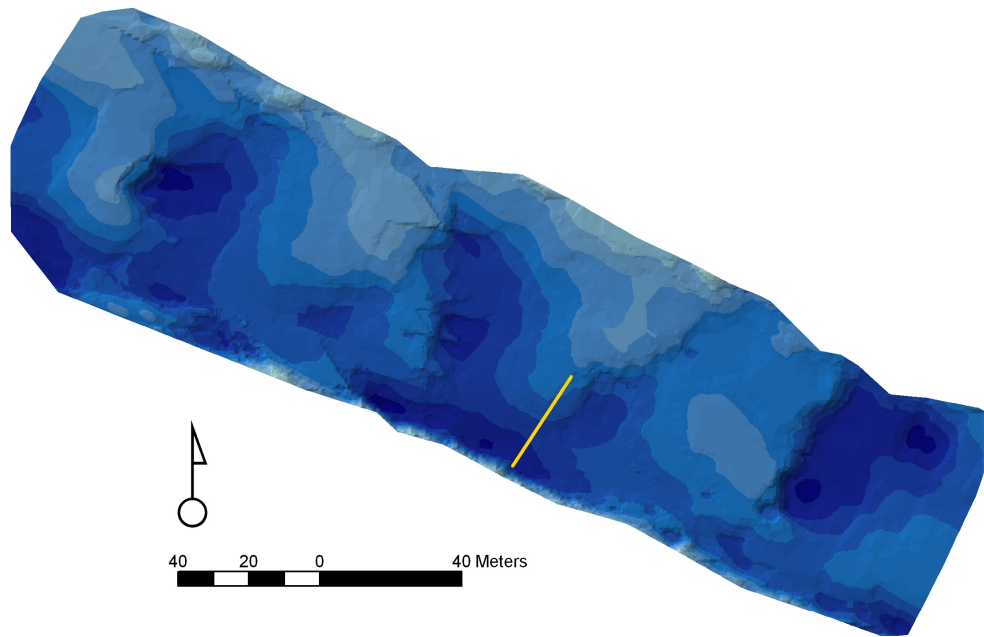


Figure 5. Bathymetry of the Roanoke River at the study site, overhead view. Darker shades of blue represent deeper water. The yellow line segment indicates the section of the channel covered by the transducer. Note that the deepest water at the transducer location is near the southern shore, and the river is shallower at greater distances from the transducer.

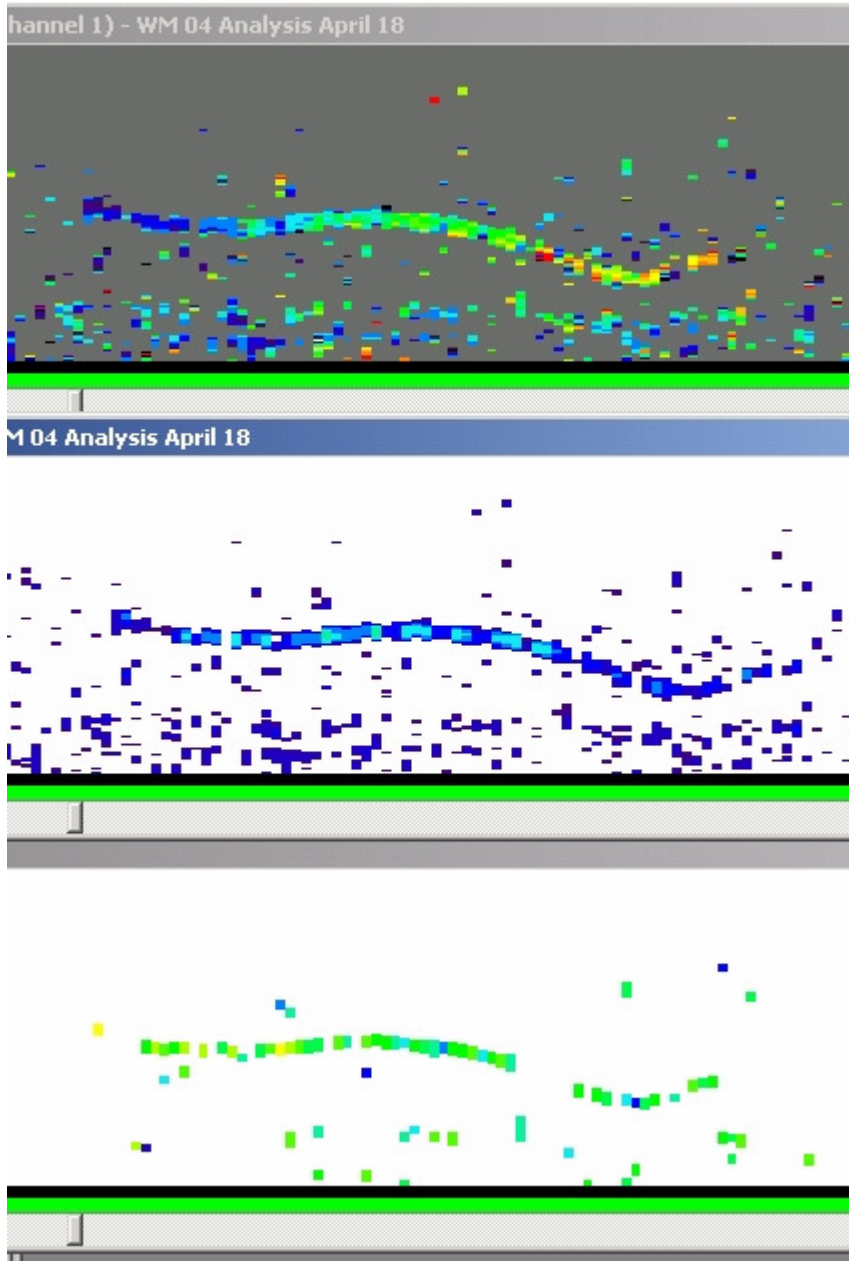


Figure 6. Data from a single fish track: direction of movement (top), target strength (middle) and single target detection (bottom) windows, as displayed within Echoview analysis software. In the upper panel, the change in color from blue to red indicates a fish moving upstream (horizontal angular position of returning echoes change from negative to positive values). In the middle panel, lighter colors indicate a more intense returning echo. The single target detection window displays returning echoes that meet a set of error-filtering criteria (Appendix Table 2).

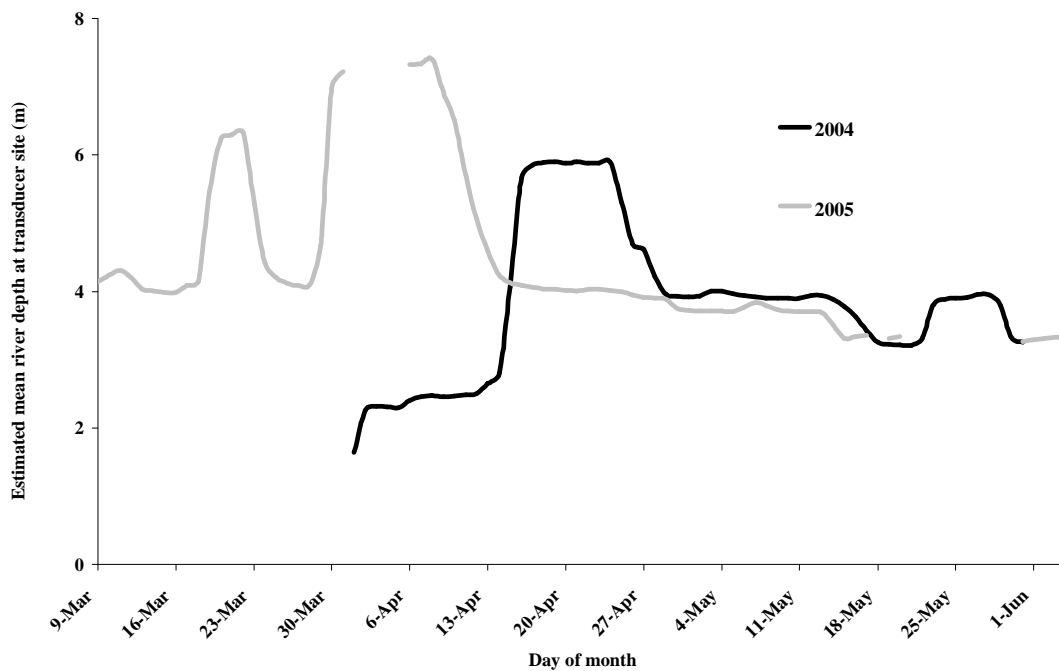
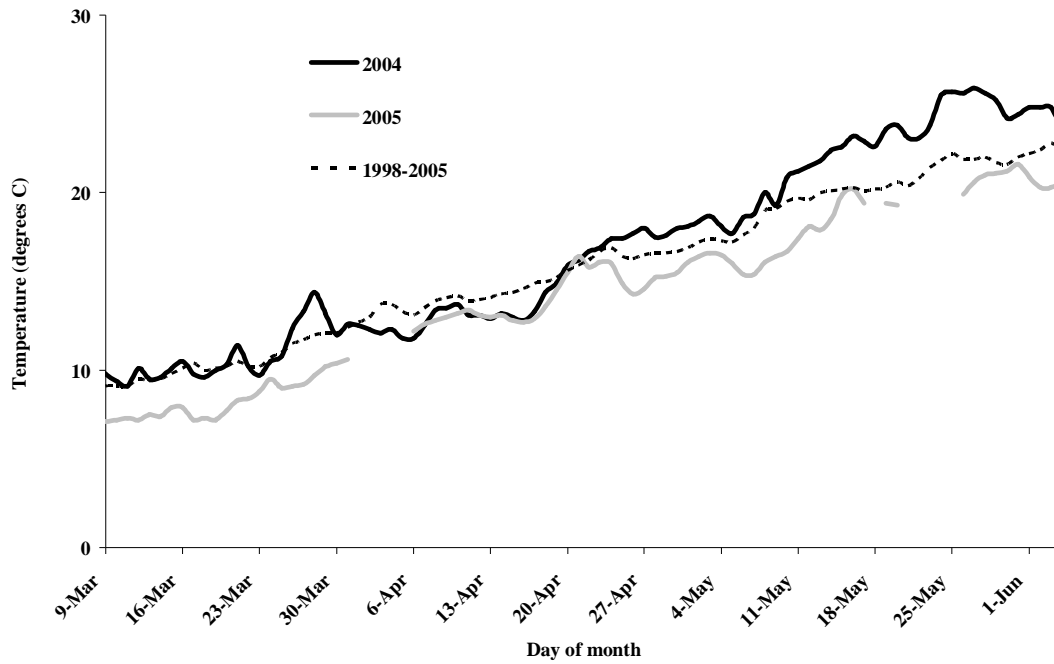


Figure 7. Estimated daily water temperature and mean river depth at the transducer location during the 2004 and 2005 study periods. Data are from the USGS gaging station at Halifax, NC (#0208062765). The upper panel includes an 8-yr average water temperature. Gaps in values are due to instrument malfunction.

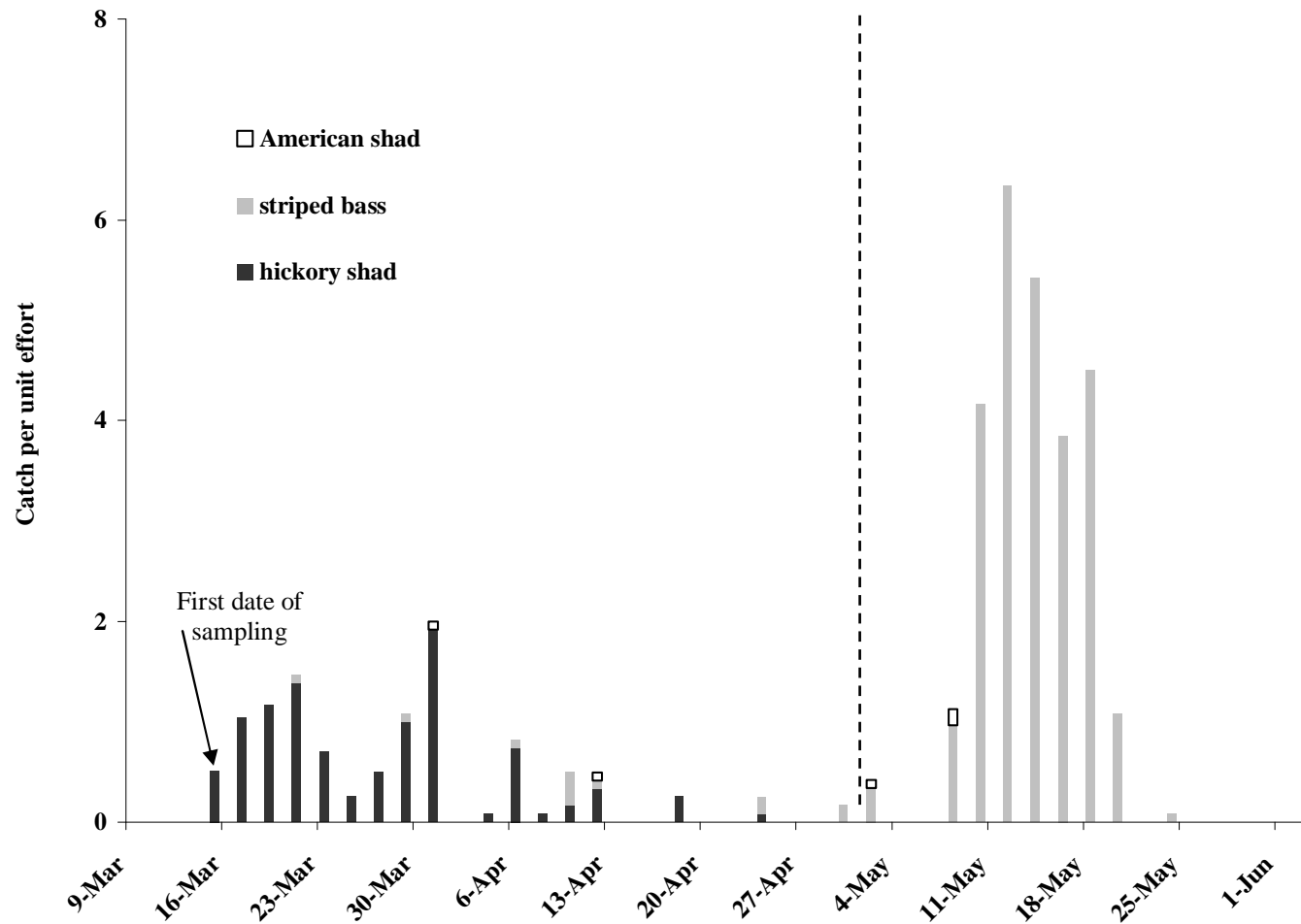


Figure 8. Gill net catch per unit effort for striped bass, hickory shad and American shad in 2004. The first date of sampling and the end of the NCWRC upper Roanoke River creel survey are noted (30 April = dashed line). CPUE is number of fish captured per 100 m drift.

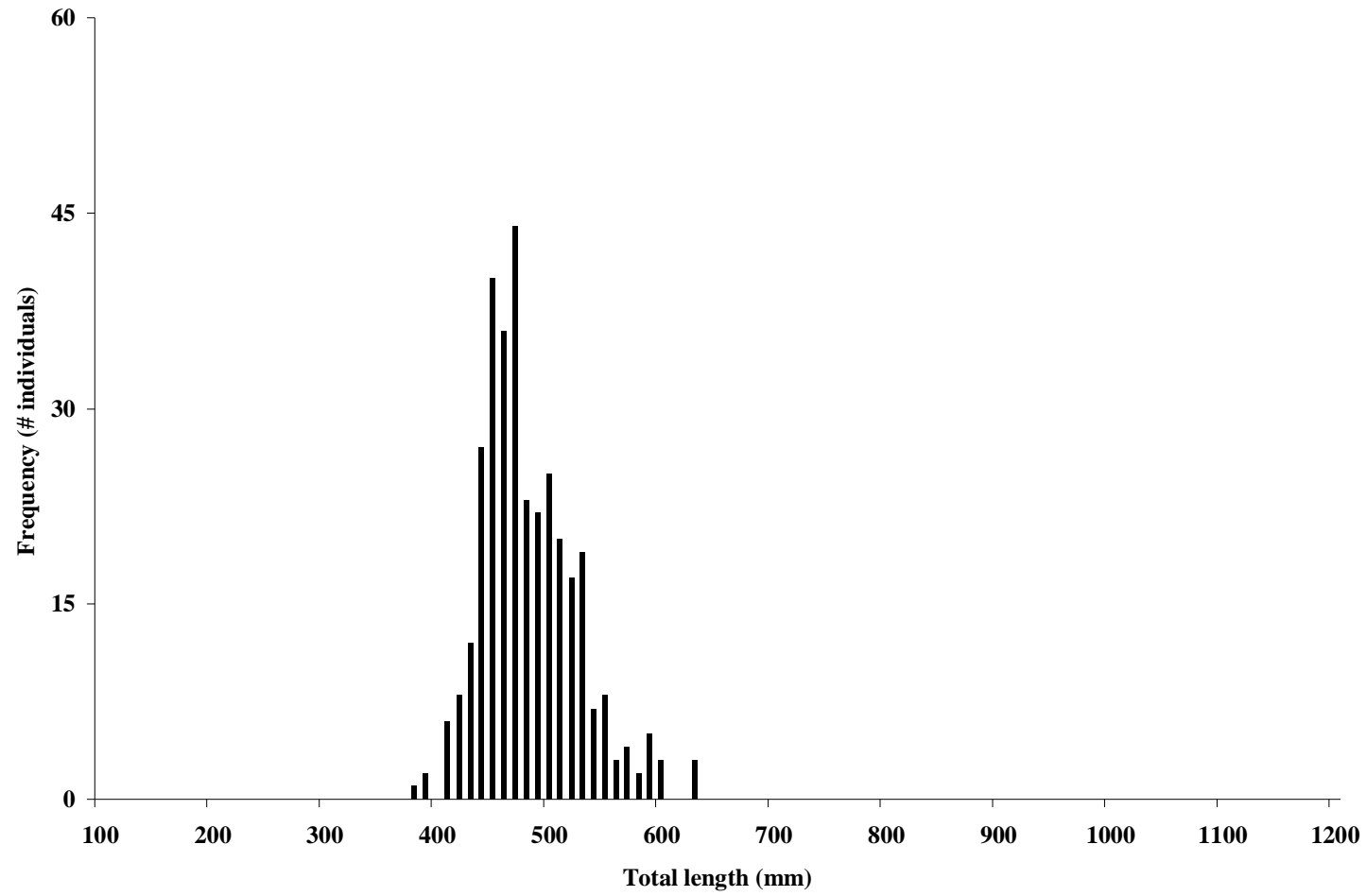


Figure 9: Length frequency distribution of striped bass captured by gillnetting in 2004.

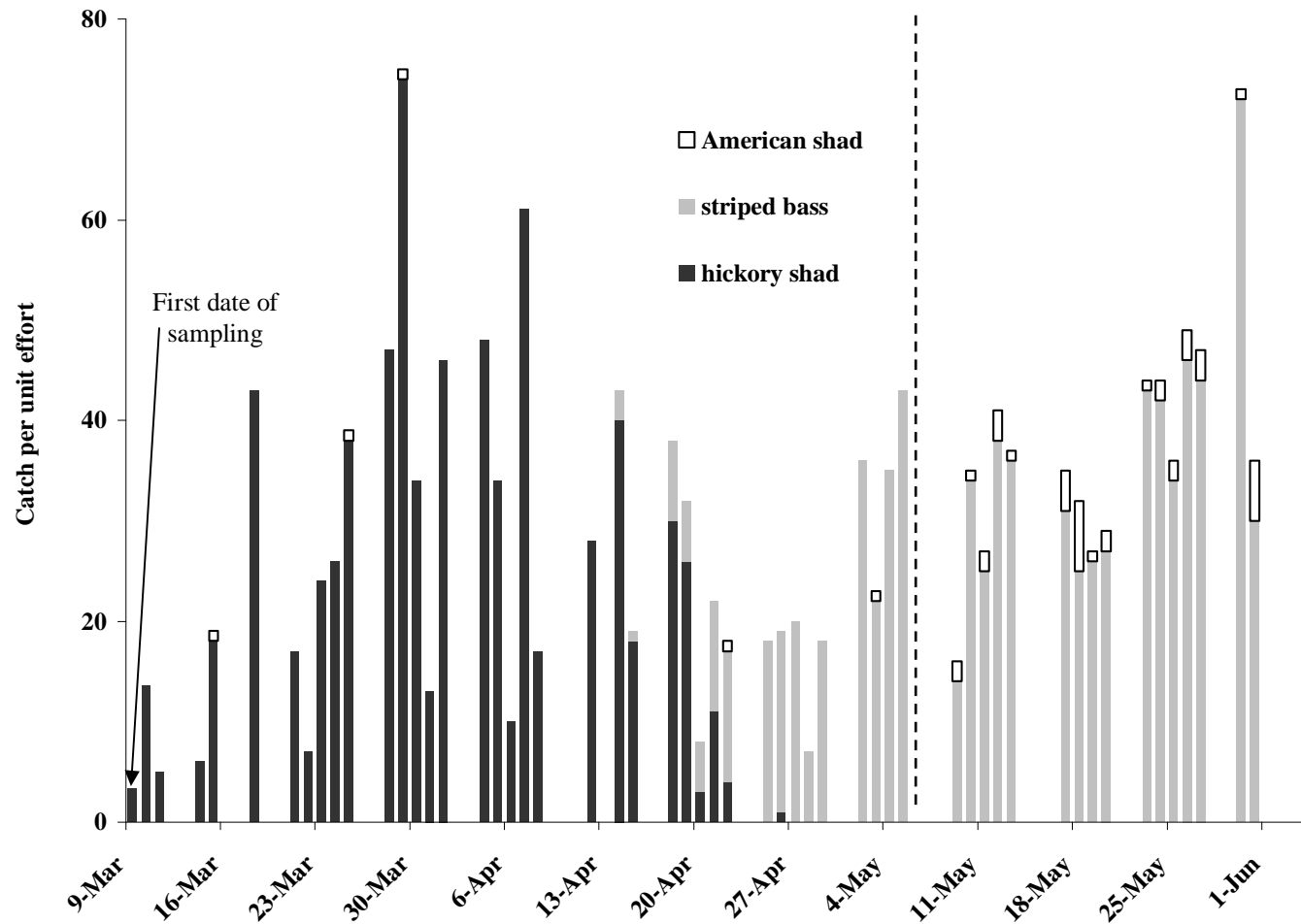


Figure 10. Boat electrofishing catch per unit effort for striped bass, hickory shad and American shad in 2005. The first date of sampling and the end of the NCWRC upper Roanoke River creel survey are noted for reference (5 May = dashed line). CPUE is number of fish captured per 2700 seconds of shock time (i.e., sum of three 900 transects: north bank, channel, south bank).

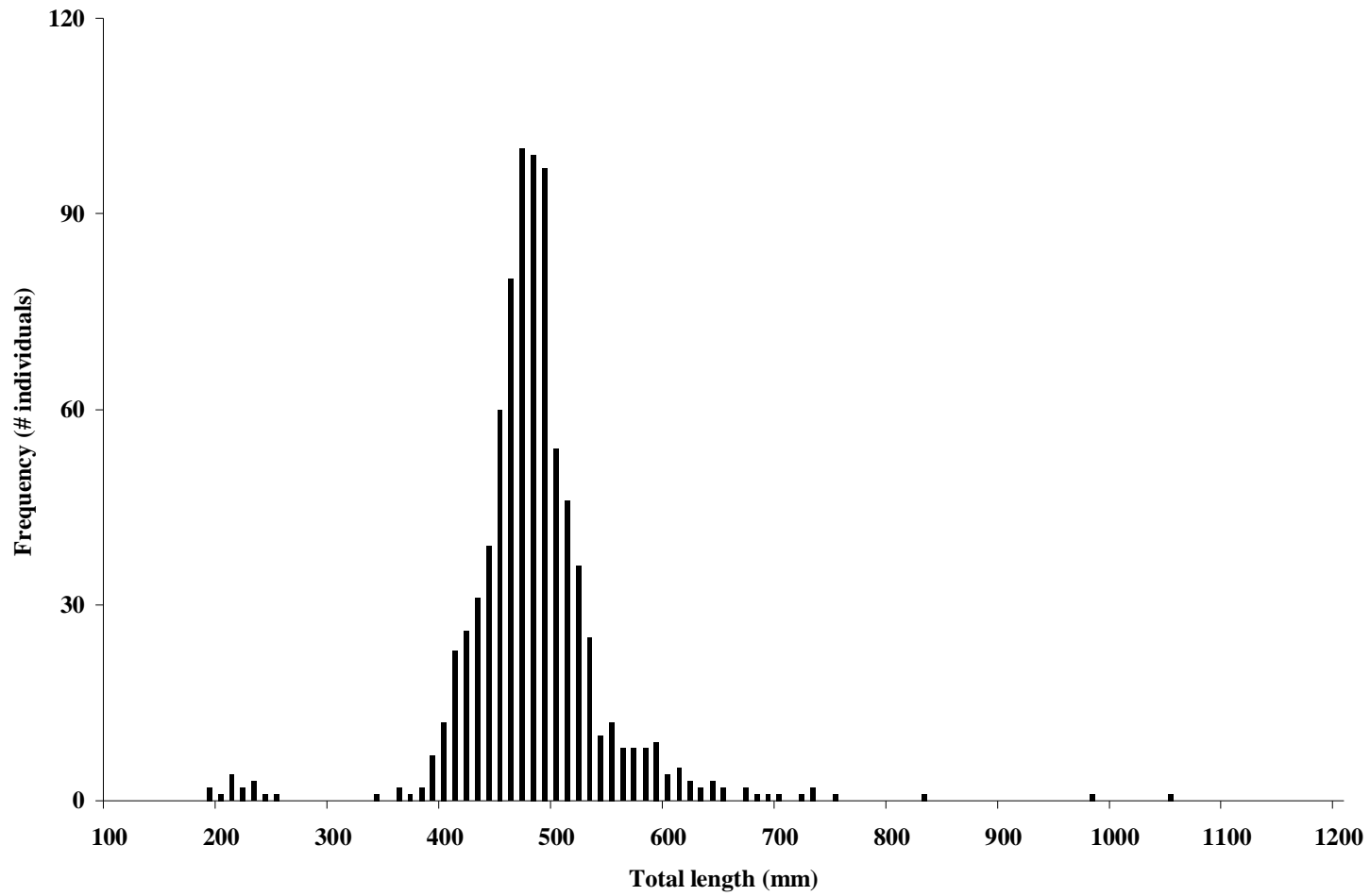


Figure 11. Length frequency distribution of striped bass captured by electrofishing in 2005.

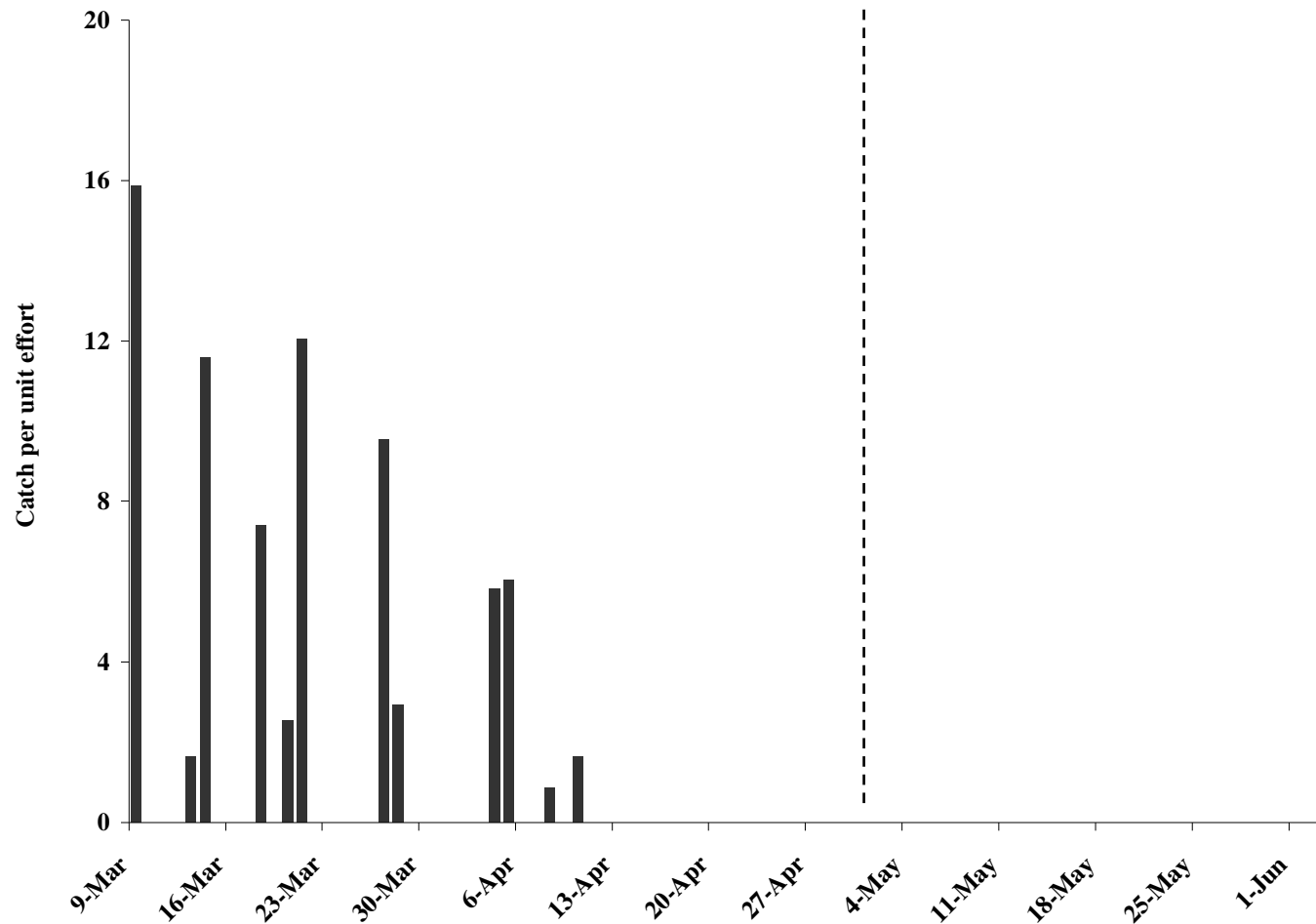


Figure 12. Hickory shad catch per angler hour data from the 2004 Roanoke River Recreational Fishery Monitoring program. Anglers were randomly interviewed at three sites in the upper Roanoke River (defined as Roanoke Rapids Lake to U.S. Highway 258 bridge near Scotland Neck, NC). Sampling took place between 1 March and 30 April.

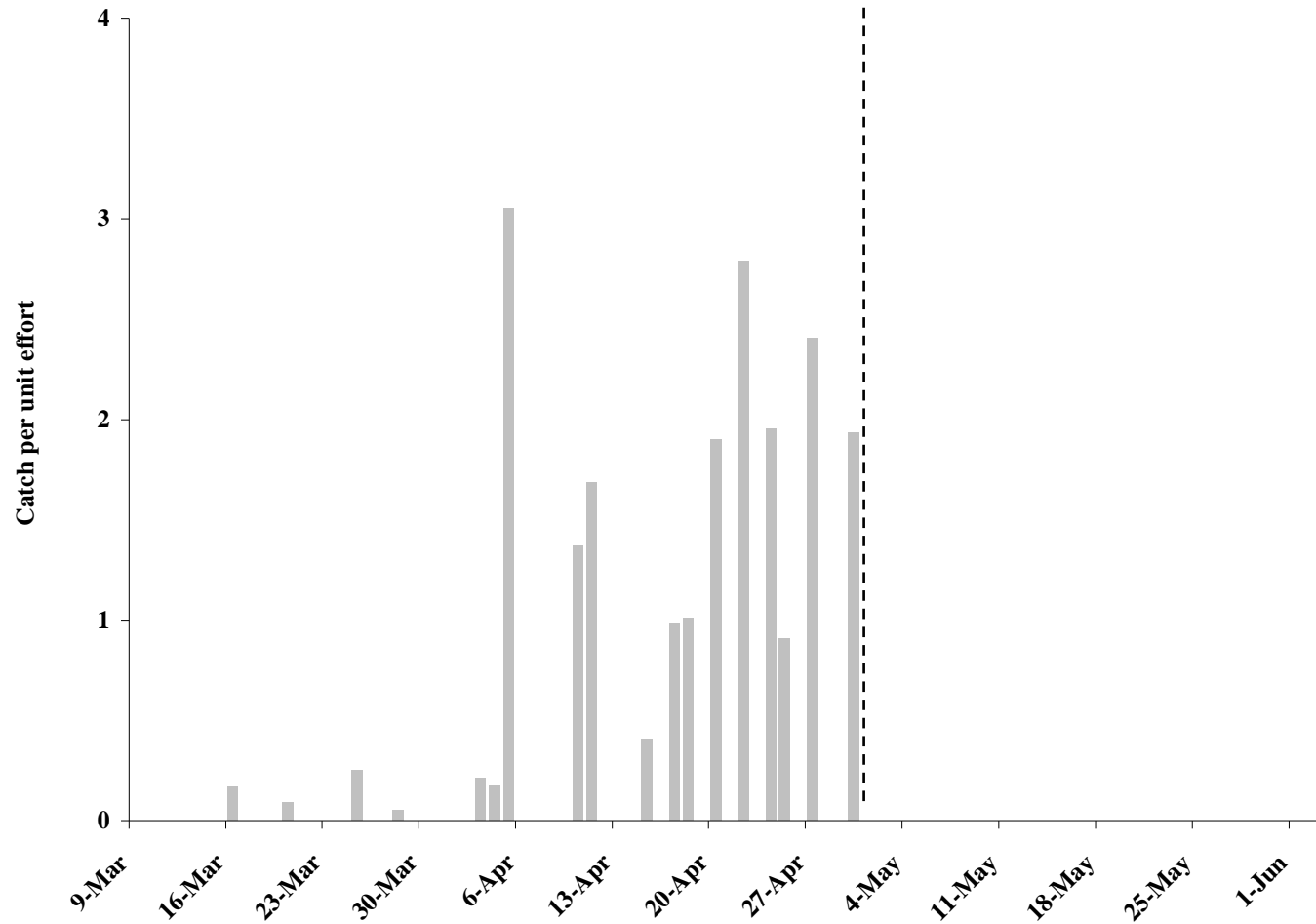


Figure 13. Striped bass catch per angler hour data from the 2004 Roanoke River Recreational Fishery Monitoring program. Anglers were randomly interviewed at 3 sites in the upper Roanoke River (defined as Roanoke Rapids Lake to U.S. Highway 258 bridge near Scotland Neck, NC). Sampling took place between 1 March and 30 April.

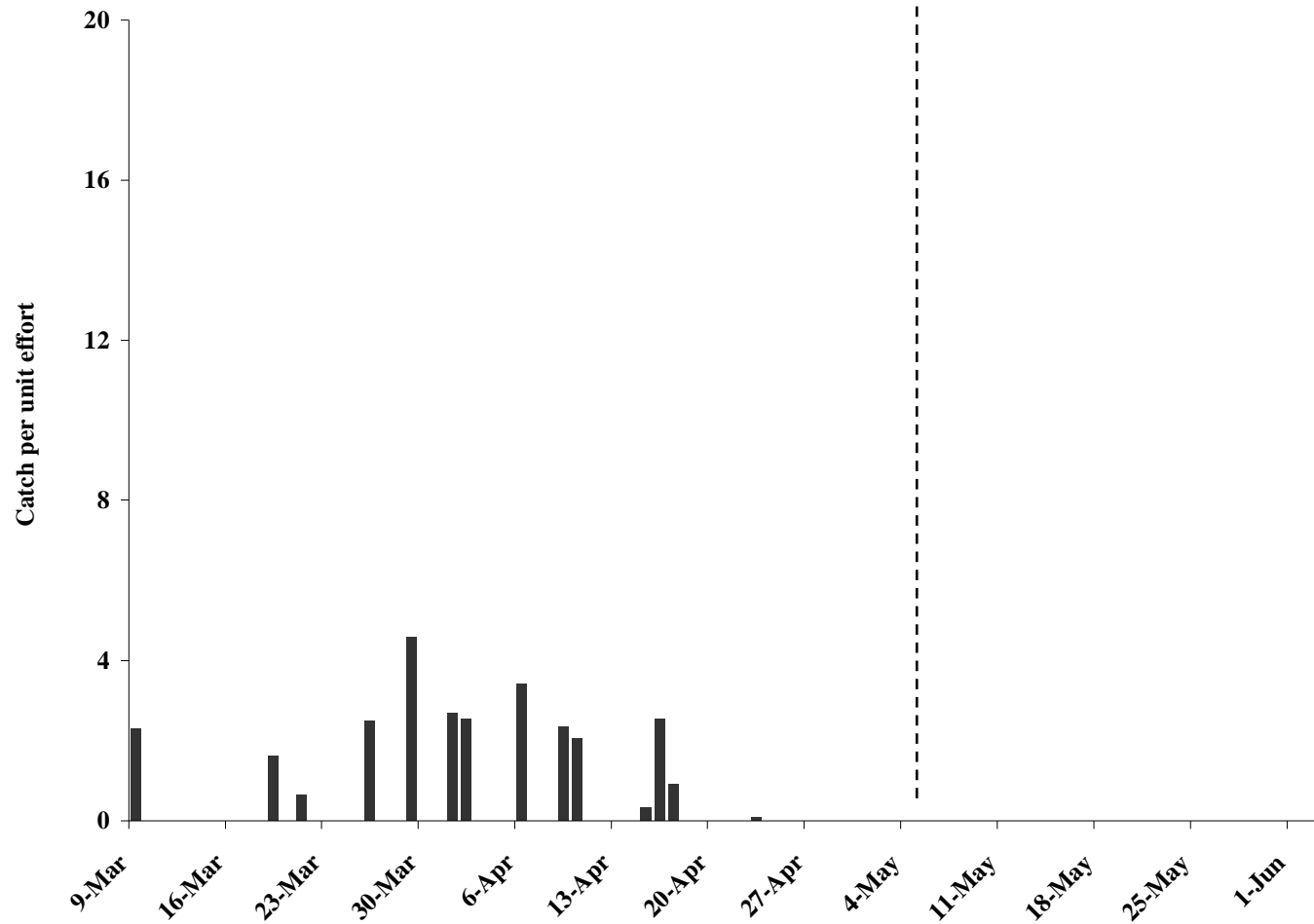


Figure 14. Hickory shad catch per angler hour data from the 2005 Roanoke River Recreational Fishery Monitoring program. Anglers were randomly interviewed at 3 sites in the upper Roanoke River (defined as Roanoke Rapids Lake to U.S. Highway 258 bridge near Scotland Neck, NC). Sampling took place between 1 March and 5 May.

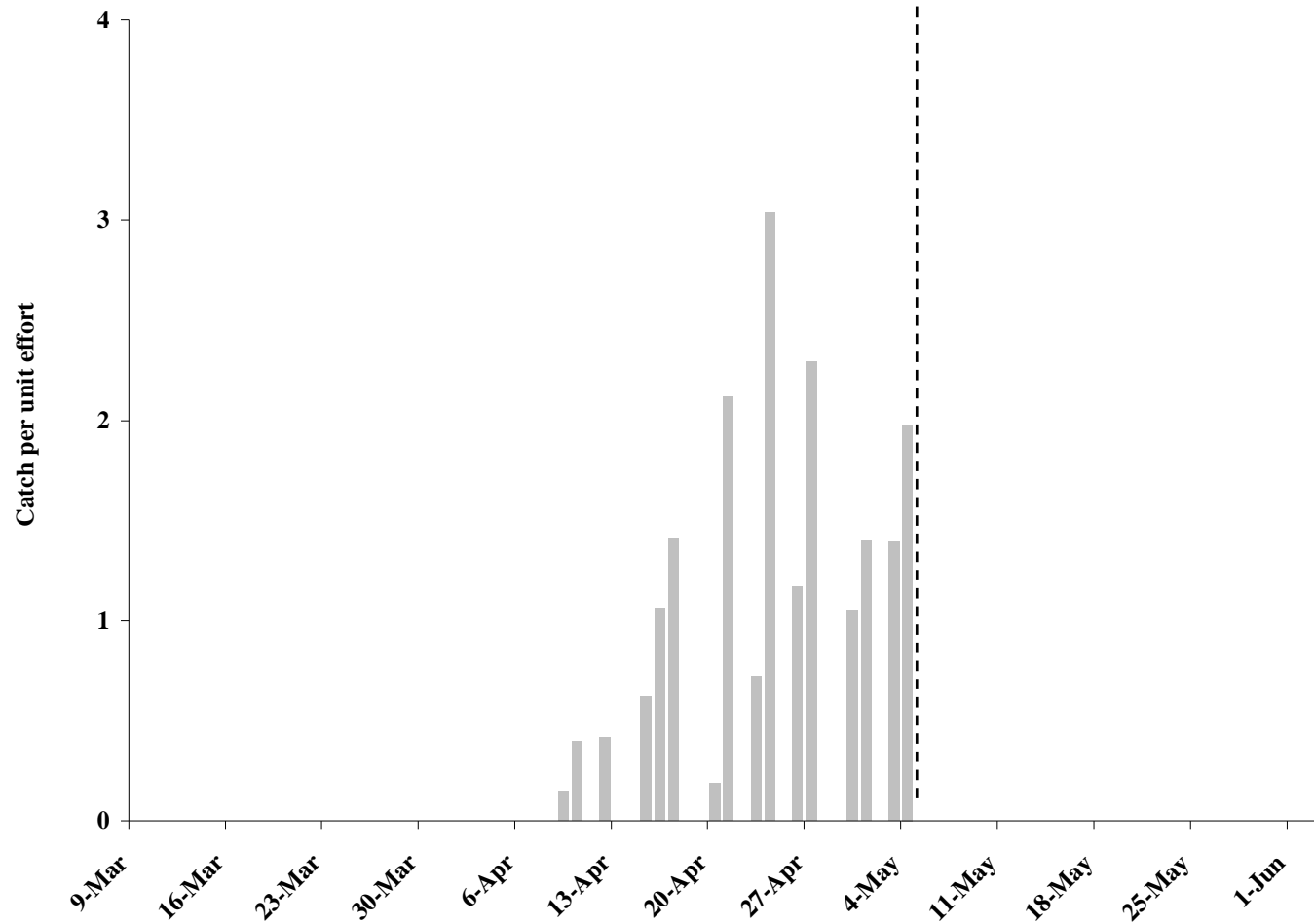


Figure 15. Striped bass catch per angler hour data from the 2005 Roanoke River Recreational Fishery Monitoring program. Anglers were randomly interviewed at 3 sites in the upper Roanoke River (defined as Roanoke Rapids Lake to U.S. Highway 258 bridge near Scotland Neck, NC). Sampling took place between 1 March and 5 May.

□ NCSU ■ Dominion

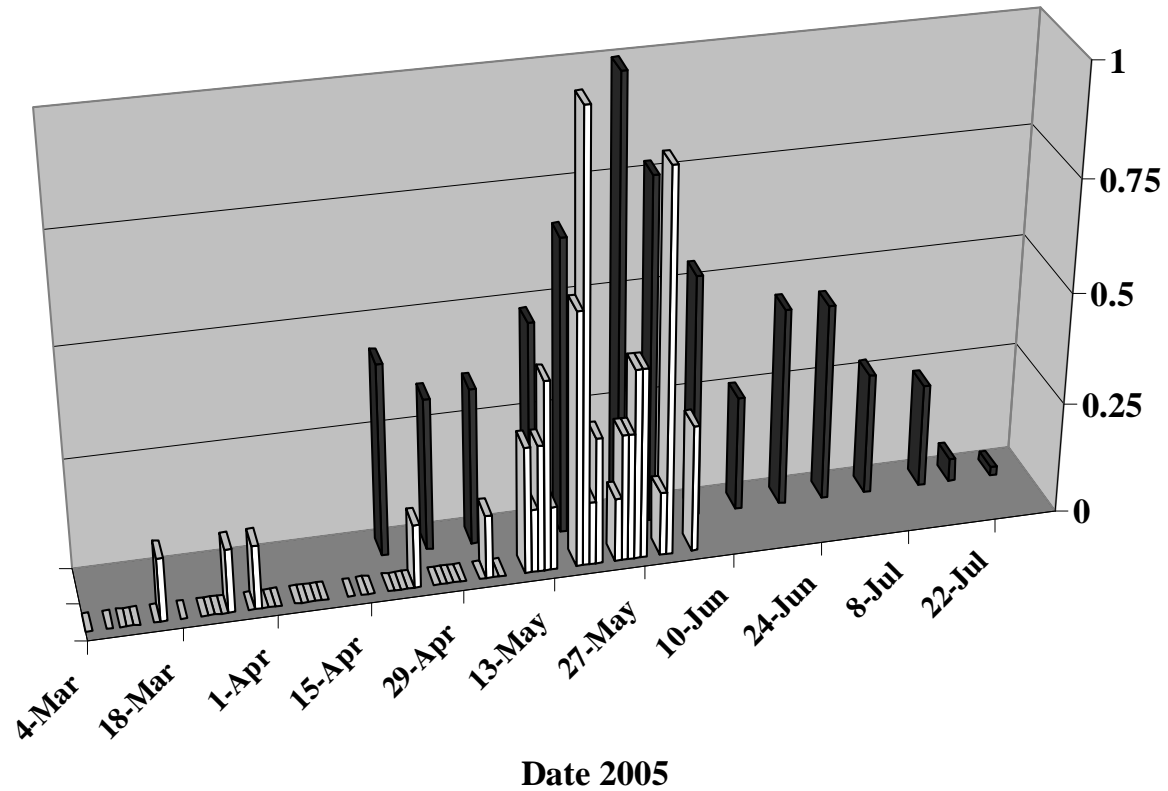


Figure 16. Comparison between 2005 American shad electrofishing catches and a separate study on the upper Roanoke River. American shad were captured by Dominion Power biologists in 2005 using similar methods, and CPUE for each survey is scaled to one for comparison. Dominion Power sampled what are considered major spawning grounds in Roanoke Rapids (rkm 218, approximate), between the Route 48 bridge and a downstream bridge owned by International Paper Company. The NCSU study (rkm 185) ended on 4 June; Dominion sampling ended 26 July.

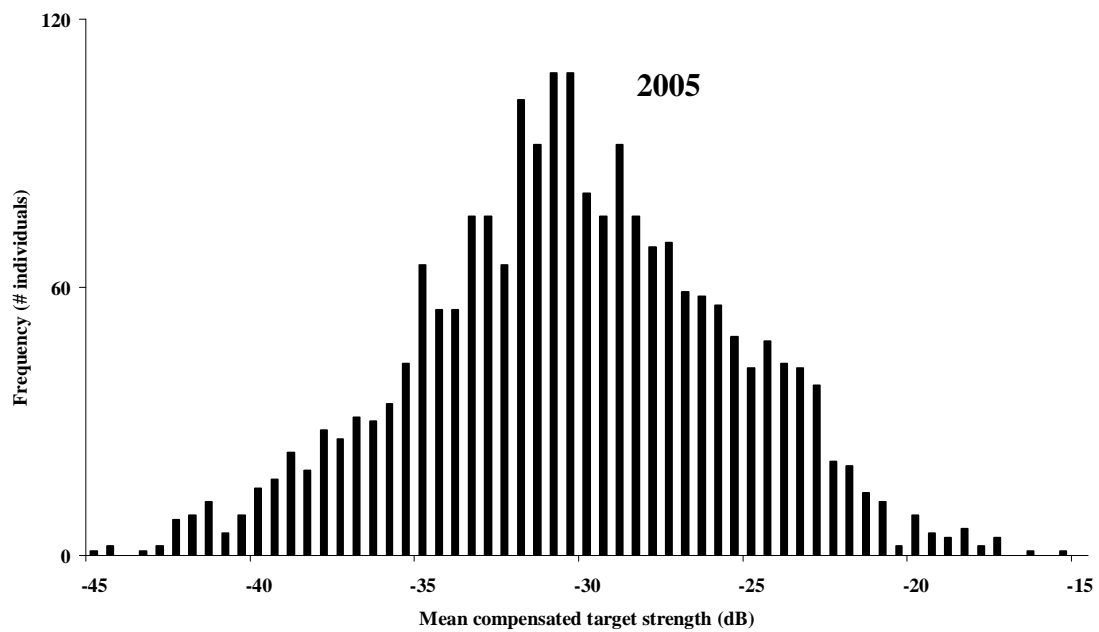
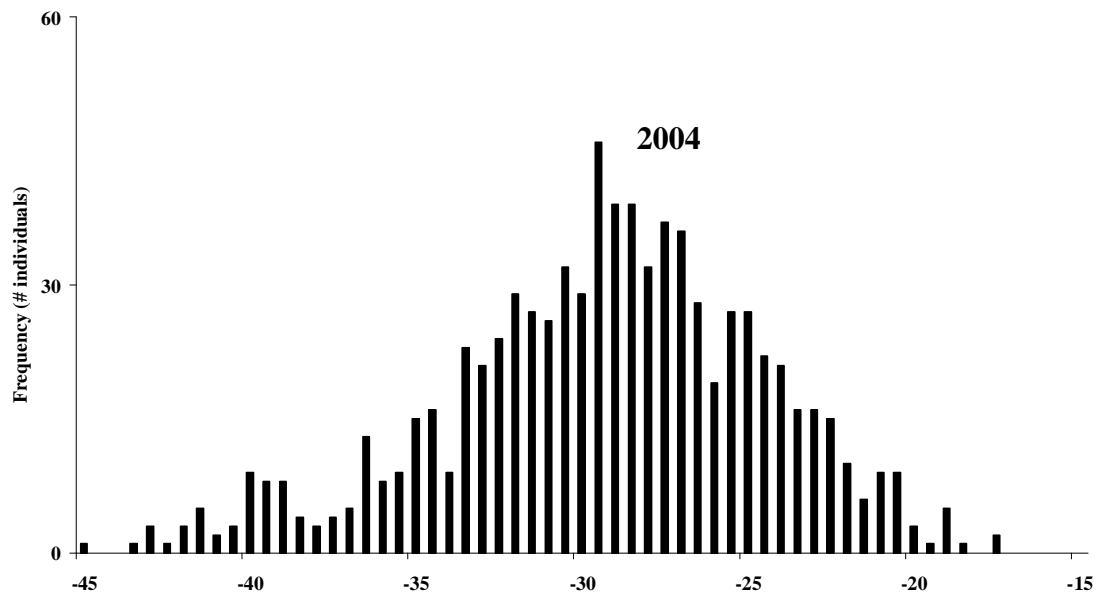


Figure 17. Frequency distributions of mean compensated target strengths from upstream migrating fish in 2004 and 2005.

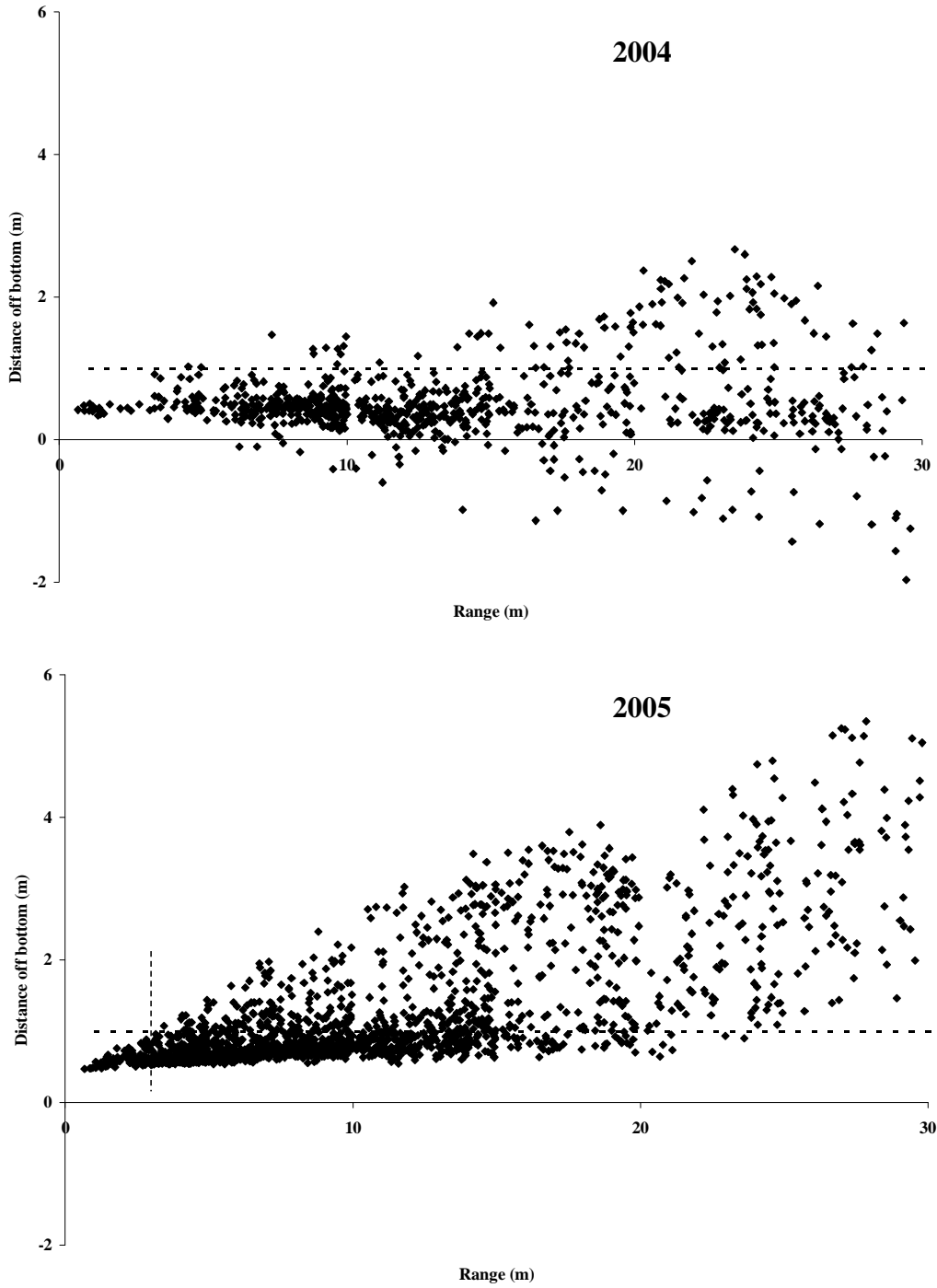


Figure 18. Estimated mean locations within the channel cross-section of $n = 808$ and $n = 2,117$ tracks of upstream migrating fish during the 2004 and 2005 field seasons. Errors in estimated position result in a few fish being located below the river bottom during 2004 (7%). These positioning errors most often occur for fish close to the bottom, and may also be due to transducer relocation following the 12 April to 16 April malfunction. Horizontal dashed lines illustrate the concentration of upstream migrating fish tracks at elevations less than 1m in both years. The vertical dashed line in 2005 demarcates a range of 3 m.

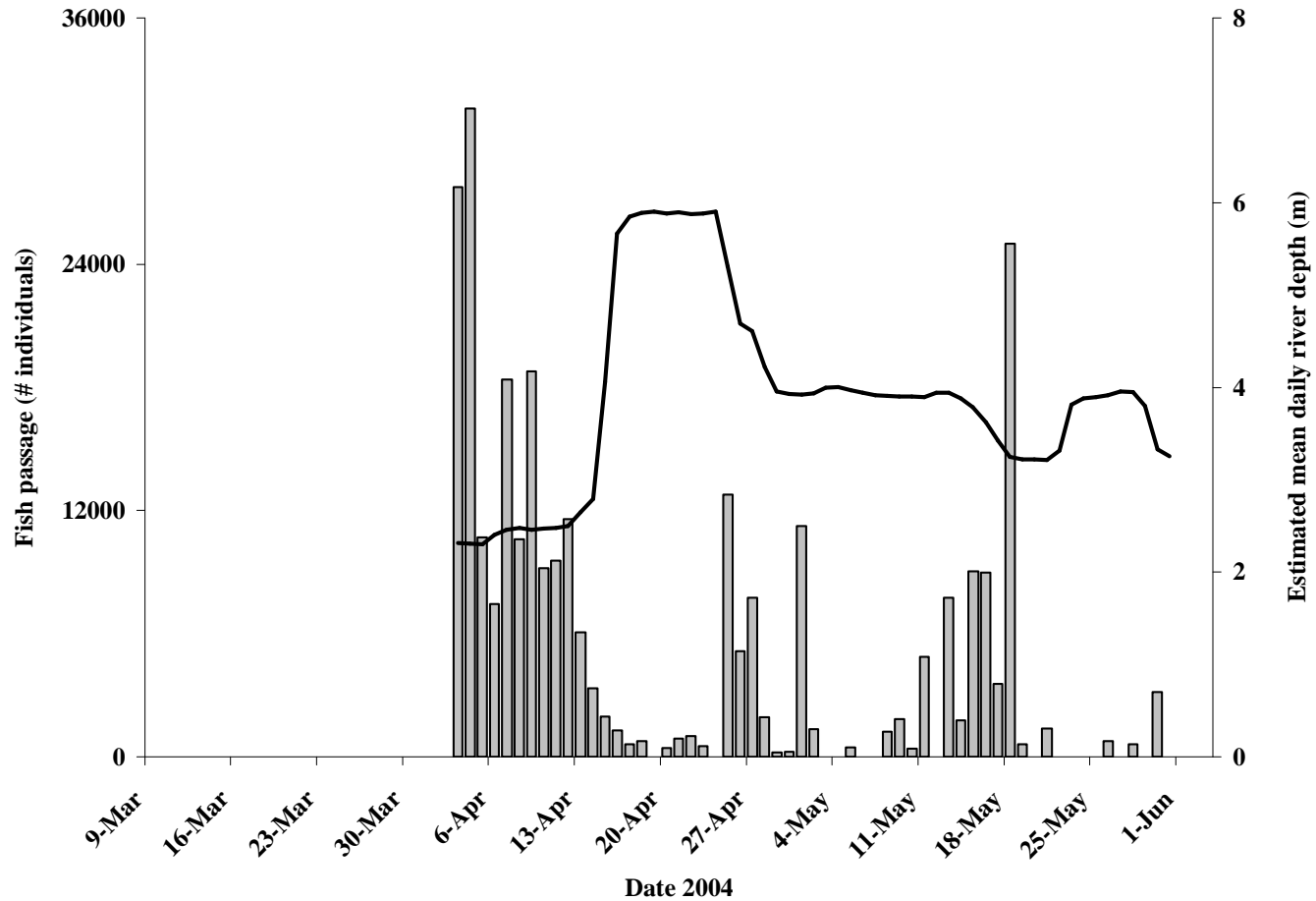


Figure 19. Daily estimated upstream fish passage (bars) for the period 3 April to 31 May, 2004 (284,289 individuals). Adjustments for missed days due to incomplete acoustic data were applied to 13-16 April.

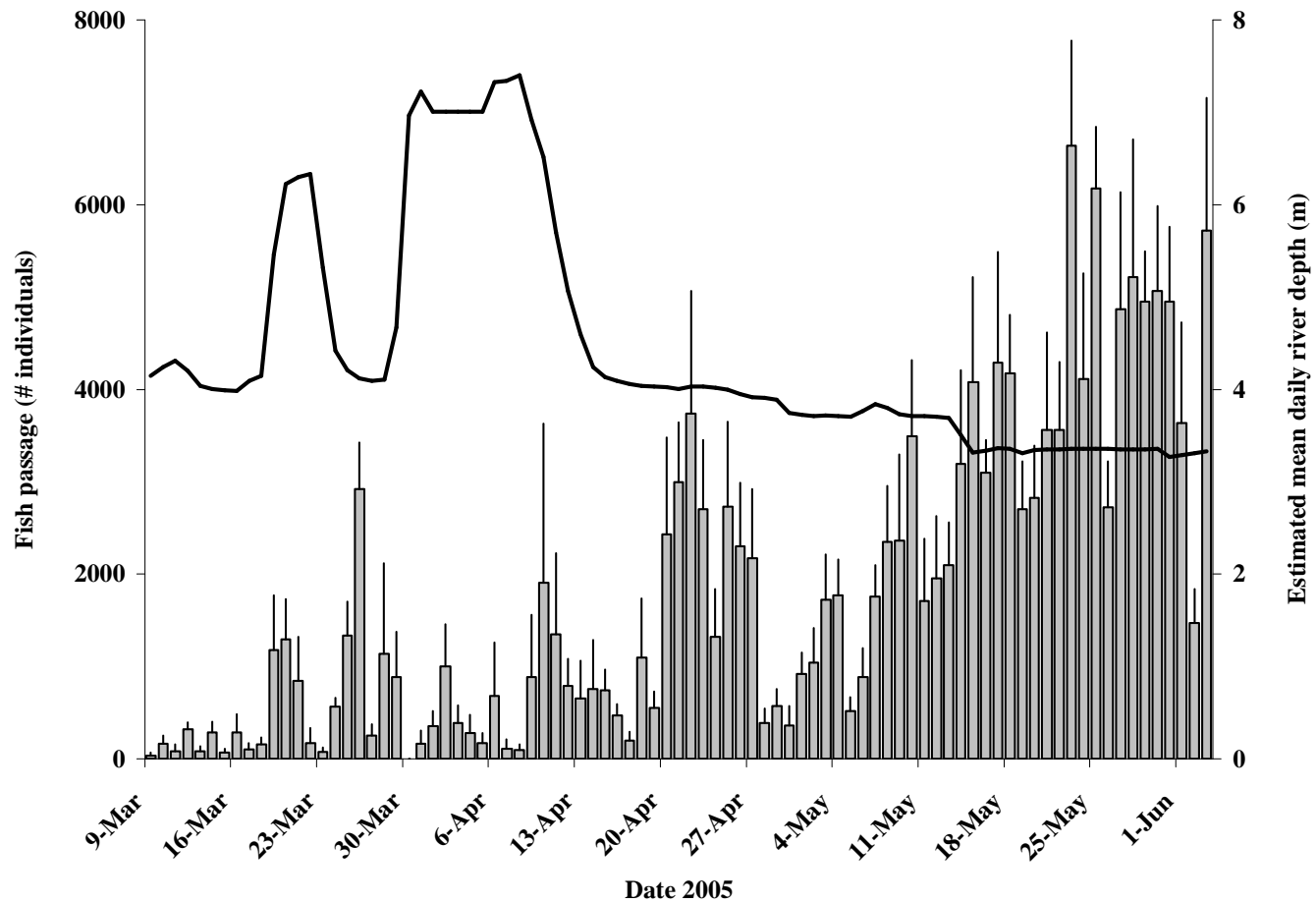


Figure 20. Daily upstream fish passage (+ SE) for the period 9 March to 3 June, 2005 (156,098 individuals \pm 6,101). Adjustments for missed days due to incomplete acoustic data were applied to 11 April, 16 April, 30 April, 1 May and 6-7 May.

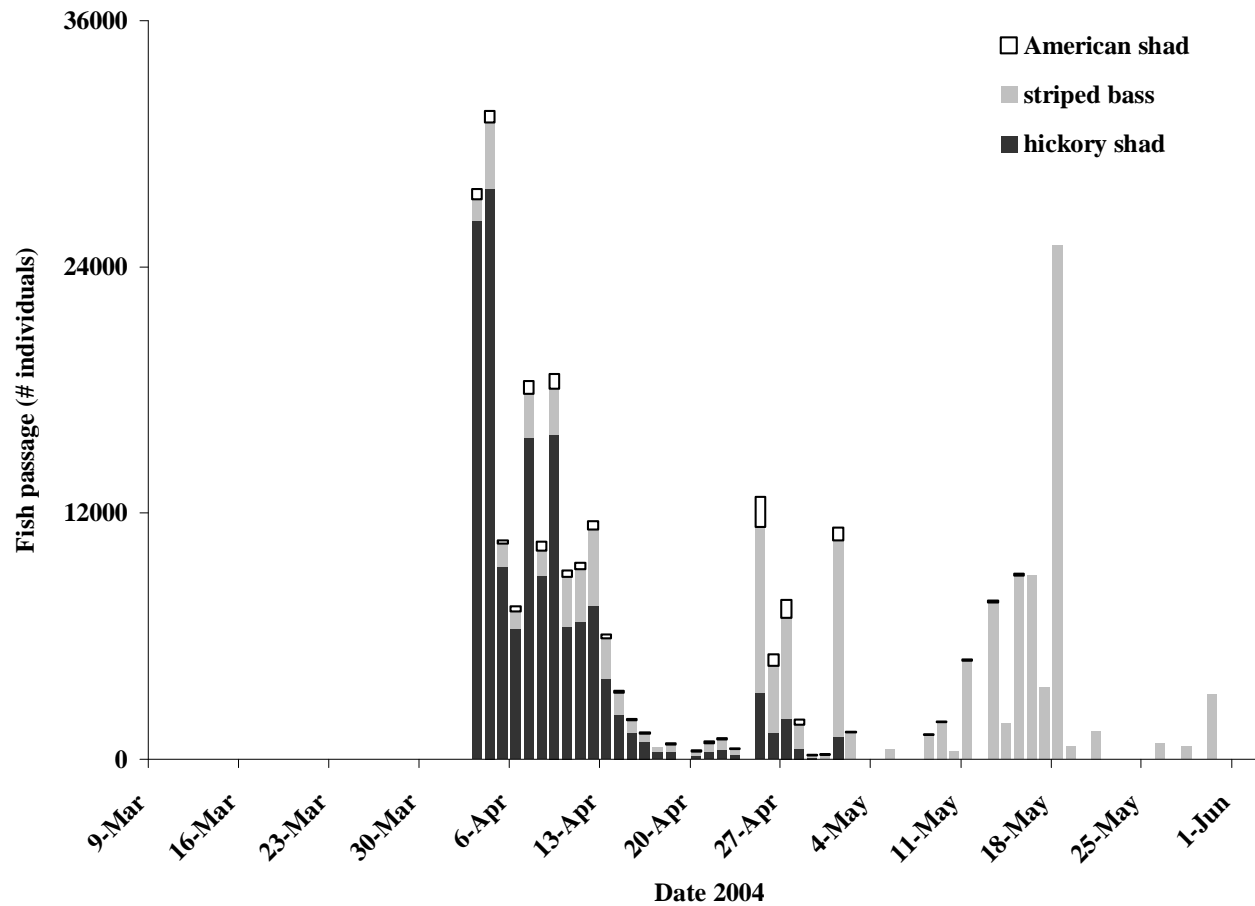


Figure 21. Hydroacoustic estimates of upstream migrating fish per day in 2004 for striped bass, hickory shad and American shad. Anadromous target species were sampled by drift gillnetting. Species proportions were then applied to raw count data by 7-day moving average.

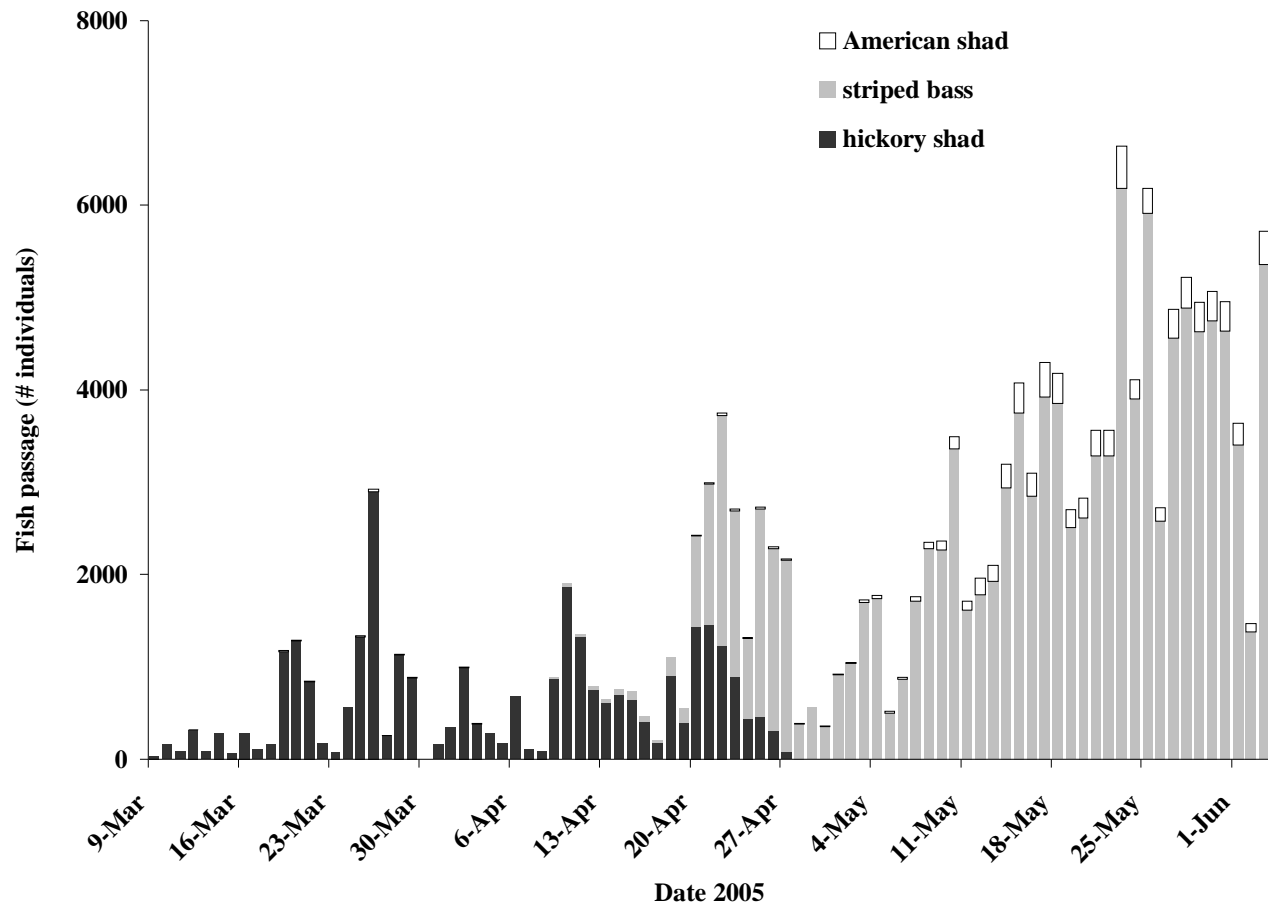


Figure 22. Hydroacoustic estimates of upstream migrating fish per day in 2005 for striped bass, hickory shad and American shad. Anadromous target species were sampled by boat electrofishing. Species proportions were then applied to raw count data by 7-day moving average.

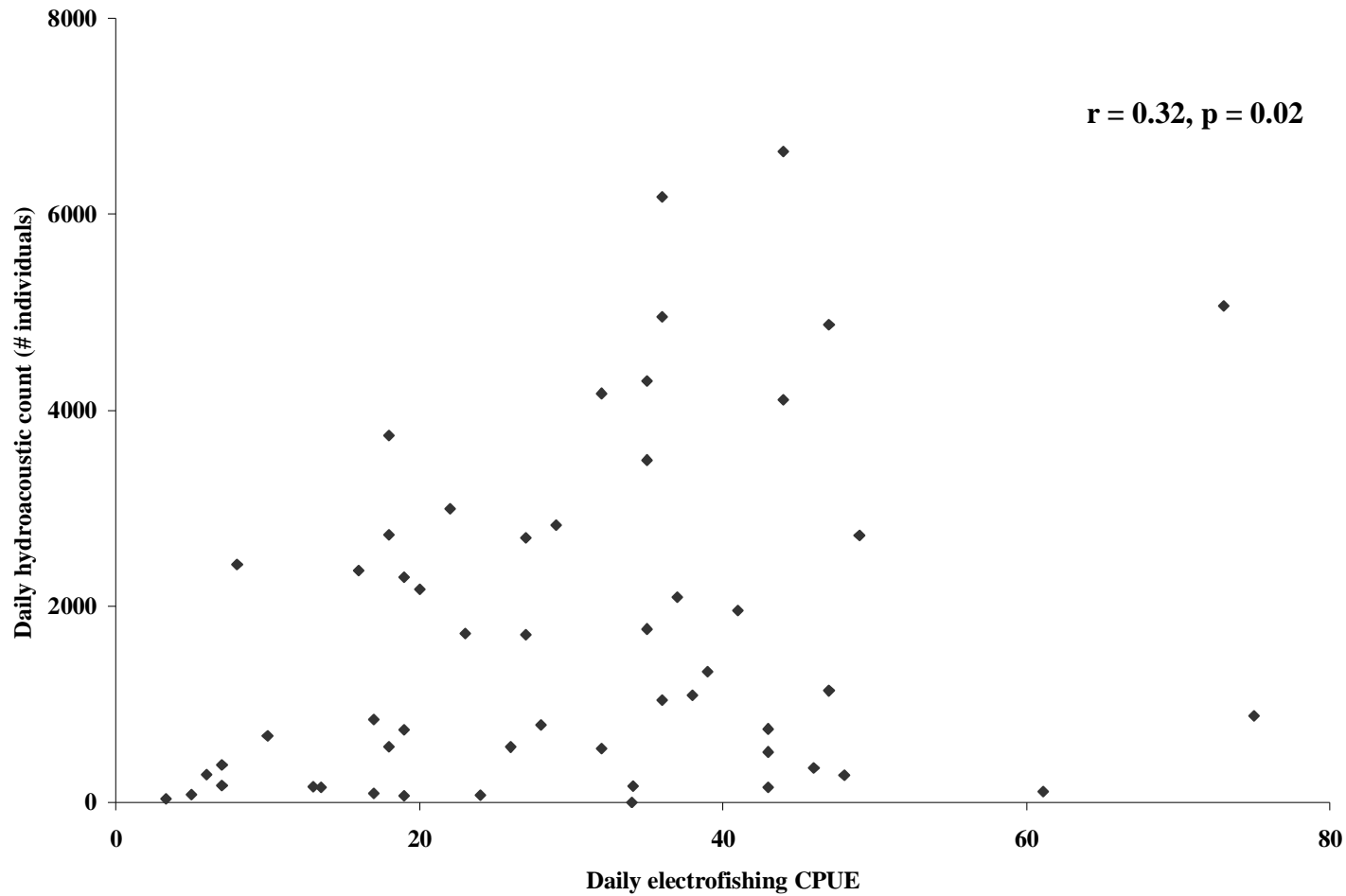


Figure 23. Significant positive correlation between 2005 daily hydroacoustic counts and electrofishing catch per unit effort. Data is from 54 days during the field season which had samples from both gears.

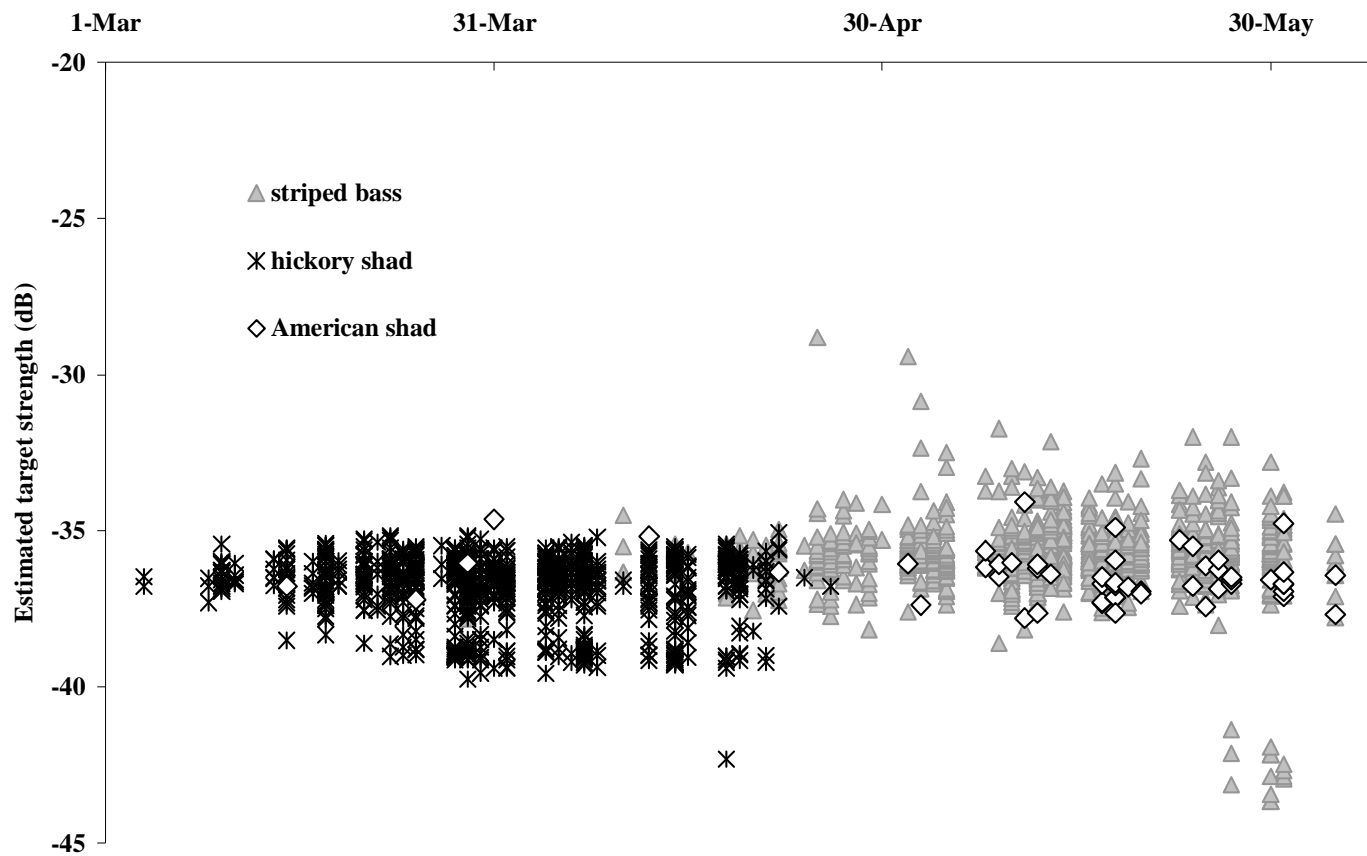


Figure 24. Individual estimated target strengths for all species captured during 2004 and 2005 species composition sampling, plotted by date. Linear conversions of total fish length in millimeters (L_{mm}) to target strength (TS) are from Love's any aspect equation ($TS = 20 * \log_{10}(L_{mm} / 10) - 69.23$).

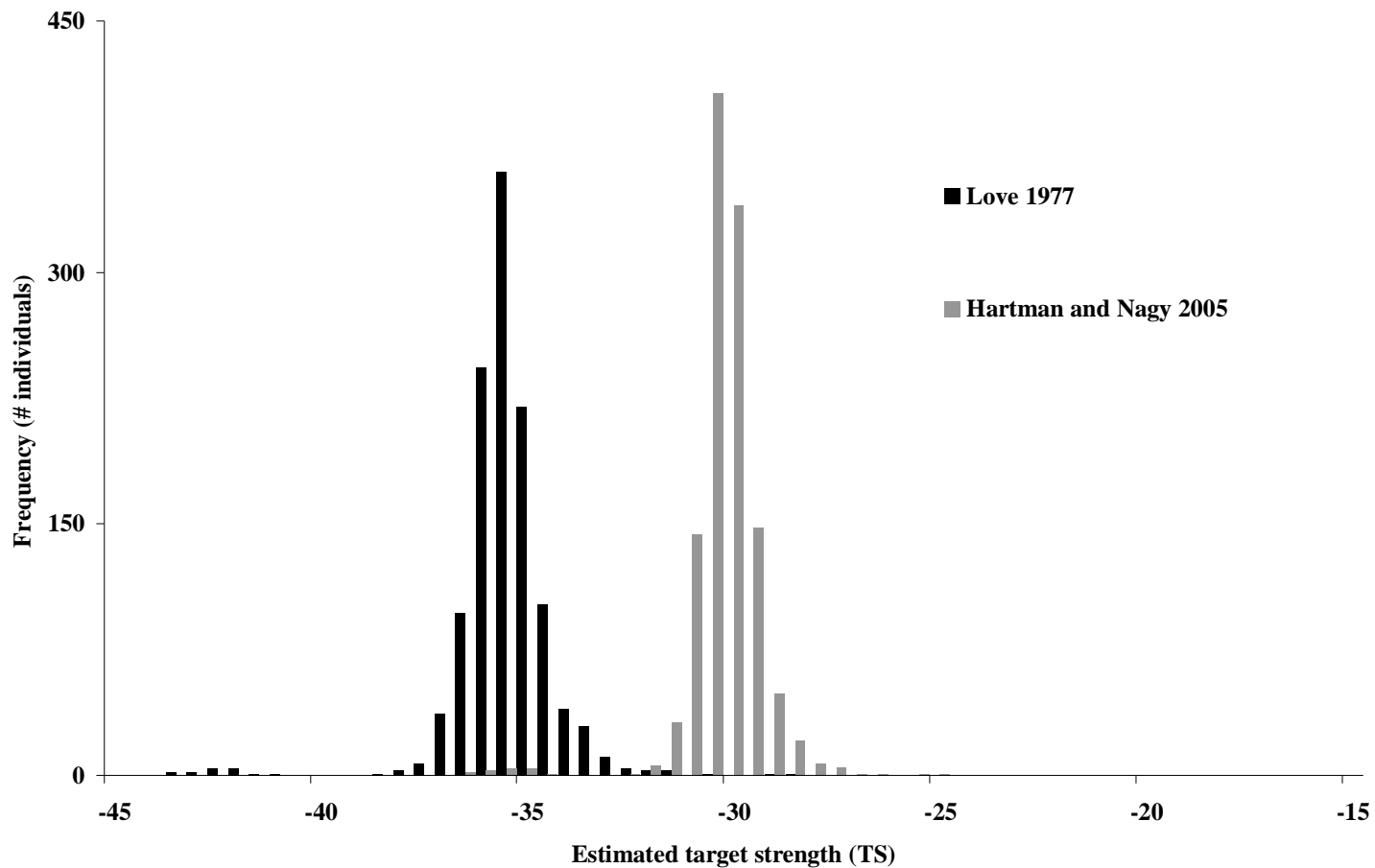


Figure 25: Frequency distributions for estimated striped bass target strengths from two years of species composition sampling. Linear conversions of total fish length in millimeters to target strength (L_{mm}) are from Love's any aspect equation ($TS = 20 * \log_{10}(L_{mm} / 10) - 69.23$) and Hartman and Nagy's dorsal aspect equation ($TS = 15.37 * \log_{10}(L_{mm} / 10) - 56.26$).

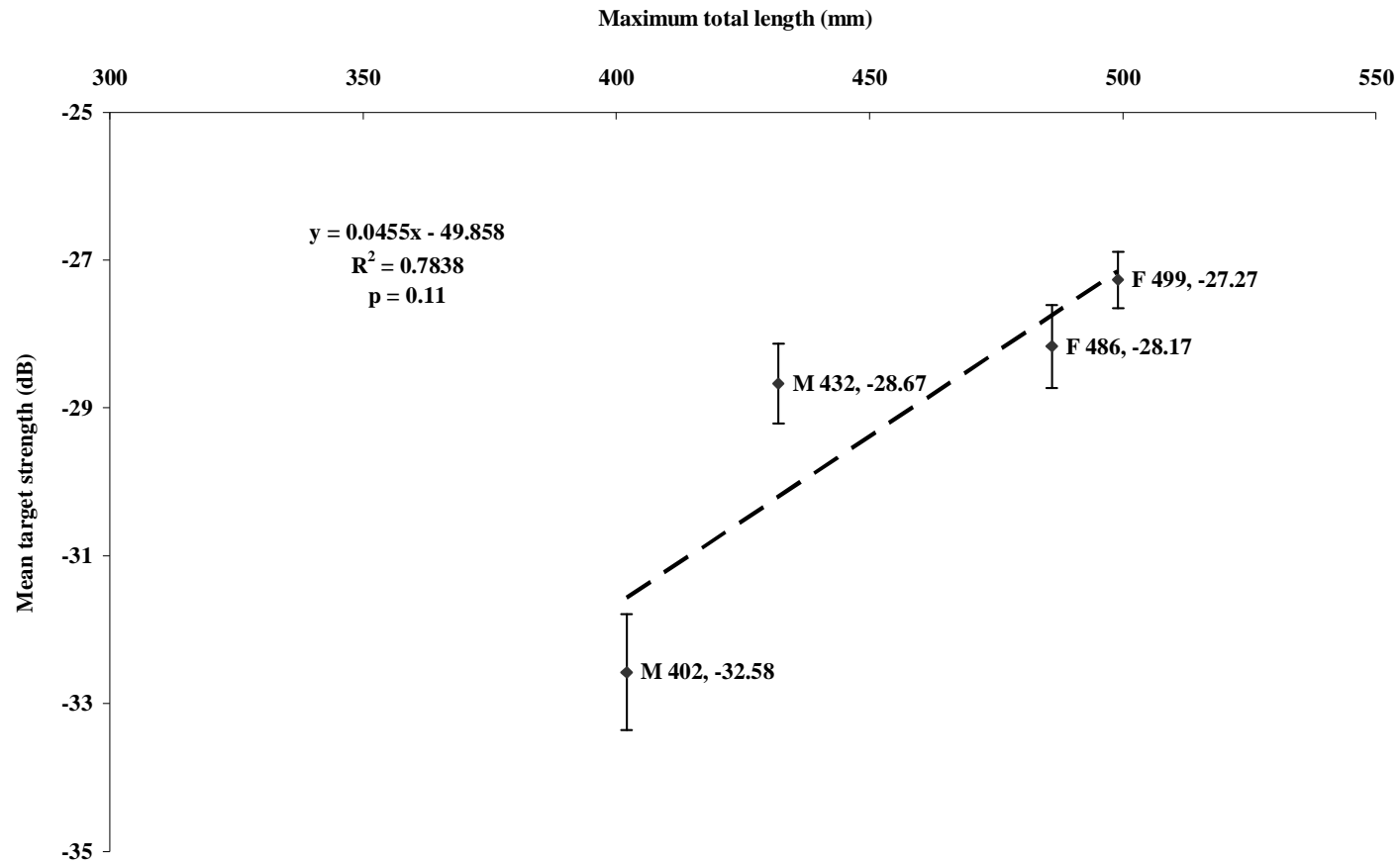


Figure 26: Measured average target strength (\pm SE) for four suspended American shad during experiments on 16 and 22 June, 2005. Maximum total length is plotted against mean side-aspect target strength for two male and two female fish (individual values are next to data points). The linear relationship was not significant.

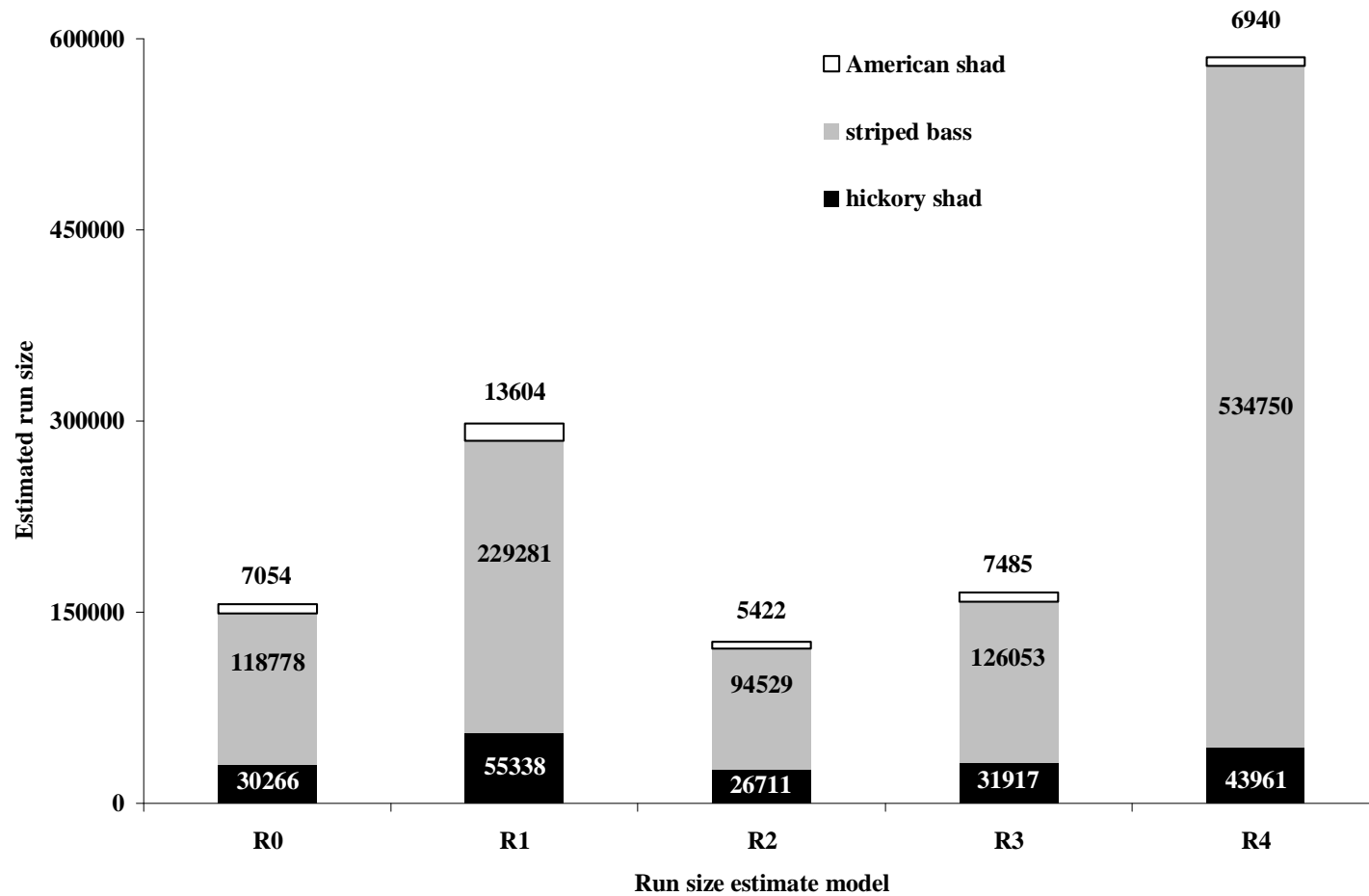


Figure 27. Alternate run sizes calculated to evaluate changes to the assumptions of the run size model (see Methods section for description of each estimator).

APPENDICES

Appendix Table 1: 2004 and 2005 Fish Track Detection variable property settings.

		Major (x) Axis	Minor (y) Axis	Range (z) Axis
Algorithm	Alpha	0.4	0.5	0.7
	Beta	0.1	0.2	0.1
	Exclusion distance (m)	1.0	1.0	0.2
	Missed ping expansion (%)	0	0	25
Weights	Major axis	0		
	Minor axis	0		
	Range	1		
	TS	0		
	Ping gap	0		
Track Acceptance	Min number single targets in track	6		
	Min number of pings in track (pings)	3		
	Max gap between single targets	5		

Appendix Table 2: 2004 and 2005 Single Target Detection variable property settings.

Single Target Detection Parameters		
	TS threshold (dB)	-50.0
	Pulse length determination level (dB)	6.0
	Minimum normalized pulse length	0.4
	Maximized normalized pulse length	2.0
	Beam compensation model	Biosonics
	Maximum beam compensation	20.0
	Maximum SD of minor axis angles (Deg)	2.0
	Maximum SD of major axis angles (Deg)	2.0
Exclusion	Exclude targets above line	none
	Exclude targets below line	none