ABSTRACT

BOWMAN, STEPHAN W. American Shad and Striped Bass Spawning Migration and Habitat Selection in the Neuse River, North Carolina.

Chair of Advisory Committee: Joseph E. Hightower

In 1952, a low-head dam was constructed at river kilometer (rkm) 225 on the Neuse River, NC, limiting migration of anadromous fishes beyond that point. In May of 1998, the dam was removed, giving improved access to 127 rkm of potential spawning habitat. We utilized radio telemetry during 1999 and 2000 to quantify the effects of dam removal on striped bass (*Morone saxatilis*) and American shad (*Alosa sapidissima*) spawning migrations and habitat used. Locations of telemetered striped bass and American shad were monitored continually throughout the spawning season. Spawning microhabitat utilized by American shad was compared to that available to them on the spawning grounds. No spawning habitat data were collected for striped bass as they were widely distributed throughout the river and spawning was not observed. Of 22 telemetered American shad providing useable data, 12 migrated beyond the former dam site. The average maximum distance migrated in 1999 and 2000 was 226 and 251 rkm, respectively. Of 23 striped bass providing usable data, 15 migrated beyond the former dam site. The mean maximum distance migrated by striped bass in 1999 and 2000 was 218 and 250 rkm, respectively. In both years of this study, the primary American shad spawning grounds were located at rkm 239, 14 rkm above the former dam site. Compared to available habitat, American shad used relatively coarse substrates consisting of gravel, cobble, and boulder. They also used intermediate current velocities (0.20-0.60

m/s) and depths (50-125 cm). The habitat they used after the removal of the dam, even though farther upstream, was similar to the habitat utilized prior to its removal.

AMERICAN SHAD AND STRIPED BASS SPAWNING MIGRATION AND HABITAT SELECTION IN THE NEUSE RIVER, NORTH CAROLINA

by
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BIOGRAPHY

I grew up in Kitchener, Ontario, Canada, and I reeled in my first fish while I was still wearing diapers; and thus my love for fishing was born. Despite my Canadianess, I didn't play hockey as a kid; in fact, I was a bit of an ankle-skater. Instead, I spent much of my time messing around in the local creek (much to my Mother's dismay), collecting dace, leeches, crayfish and other assorted organisms (My Father once paid me ¢10 a leech for walleye bait. I don't think he ever figured out what he was going to do with $20 worth of leeches). These were my first explorations into the world of aquatic ecology.

After high school, I migrated from Kitchener to Lindsay, Ontario, where I received a Fish and Wildlife Technologist Diploma from Sir Sandford Fleming College. I quickly realized that I wasn't ready to emerge into the real world, and so I continued my studies at Trent University in Peterborough, Ontario, where I received a degree in Biology/Environmental Sciences. Shortly after I finished my undergrad, Joe Hightower accepted me as a graduate student here at NC State, and I've spent the last 2 years pleasurably following striped bass and American shad in the Neuse River. I have no idea what I'm going to do now, but since I didn't apply to any Ph.D. programs, it looks like I might have to return to Canada and find that job that I've spent the last 10 years avoiding.

One quick question - Does anybody ever read these things?

ACKNOWLEDGMENTS

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INTRODUCTION

Historically, American shad (*Alosa sapidissima*) played a key role in U.S. coastal economies. In 1896, as many as 24,708 individuals were employed in the American shad fishery along the coast (Stevenson 1899). However, the commercial harvest peaked in the late 1800s (St. Pierre 1979), and since that time harvest of American shad has generally undergone a steady decline. In the early 1970s, catches of American shad declined even further, which led to the requirement of each state to develop a Fishery Management Plan under the Atlantic Coastal Fisheries Cooperative Management Act (ASMFC 1998).

As American shad catches were declining, striped bass (*Morone saxatilis*) catches were following an opposing trend. Between 1924 and 1973, there was a general increase in striped bass harvest along the Atlantic Coast (Strand et al. 1980; Van Winkle et al. 1979). However, throughout the 1970s and 80s striped bass populations underwent dramatic declines as indicated by a reduction in the Atlantic Coast commercial catch from a peak of 14.7 million pounds (6.67 million kilograms) in 1973 to only 3.5 million pounds (1.58 million kilograms) by 1983 (Norton et al. 1984; USDOC and USDOI 1996). This precipitous decline resulted in strict harvest regulations along the U.S. Atlantic Coast, and many striped bass populations have since recovered from those historical lows (Field 1997; Richards and Rago 1999).

The declines in abundance of both species have been attributed to a number of factors including excessive harvest, declines in water quality, and dam construction (Worth 1882; Stevenson 1899; Merriman 1941; Rulifson 1994). Anadromous species are particularly susceptible to damming as their access to natal spawning grounds can be completely obstructed or extremely limited, given no effective provision for passage, such as fish ladders or lifts (Merriman 1941; Rulifson 1994).

Historically, the Neuse River in North Carolina supported abundant runs of both American shad and striped bass, with profitable American shad fisheries found as far upstream as Raleigh (Stevenson 1899). However, in 1952, a low-head dam (Quaker Neck Dam) was constructed near Goldsboro at river kilometer (rkm) 225 with the purpose of impounding cooling water for a steam electric plant (Walburg 1957). Tarplee and Partin (1979; 1981) suggested that the effects of Quaker Neck Dam on the anadromous fish community were negligible, but most studies have concluded that the dam restricted the access of anadromous species to their historical spawning grounds (Baker 1968; Hawkins 1980; Hammers et al. 1995; Beasley and Hightower 2000). There was some contradictory evidence that the dam offered minimal obstruction to spawning anadromous fish as they readily used the fish ladder or passed over the dam during periods of high water (Tarplee and Partin 1979; 1981). In contrast, results from the other studies indicated that only a limited number of fish used the ladder or passed over the dam.

In May of 1998, the Quaker Neck Dam was removed, thus allowing unhindered access to another 127 km of mainstem river and potential spawning habitat. American shad and striped bass should benefit from this habitat “release” due to an increase in the area in which they can spawn. In addition, American shad and striped bass may benefit from a higher proportion of quality spawning habitat upstream of the dam site (Beasley and Hightower 2000).

The objectives of this study were to evaluate the effects of dam removal on the migratory patterns of American shad and striped bass and determine how American shad spawning habitat utilization is modified in response to greater access to potentially preferred habitat. To meet these objectives, we used radio telemetry techniques to monitor migratory movements and identify spawning areas used by these species. In addition, we compared habitats used by spawning American shad with the habitat available to them on a microhabitat scale. Several studies have described general spawning habitat requirements of American shad (Ross et al. 1993; Chittenden 1975), but there is no published information on microhabitat used within a localized area where spawning is occurring. It is generally accepted that many mainstem habitats meeting basic temperature, substrate, and velocity requirements are used for spawning (Stier and Crance 1985), and Walburg and Nichols (1967) suggested that American shad were dispersed throughout much of the mainstem of the Neuse River.

Beasley and Hightower (2000) used telemetry techniques during 1996 and 1997 to examine the distributions and characteristics of American shad and striped bass spawning habitat prior to the removal of Quaker Neck Dam. American shad were only observed spawning within 1.5 km downstream and 3 km upstream of the dam. Within that area, spawners proproportionately used coarser substrates and shallower water than those found at randomly sampled locations. Striped bass were observed spawning within the first 1.5 km downstream of Quaker Neck Dam. Their spawning sites tended to have coarser substrates and higher current velocities than those found in random samples. Results of that study will provide baseline data with which our post-dam-removal data can be compared.

HYPOTHESES

Null hypotheses to be addressed in this project are given below:

(1) Striped bass and American shad migrations will not be more extensive after the removal of Quaker Neck Dam.

(2) The spawning habitat used by American shad will not differ between pre- and post-dam removal periods.

(3) Within identified spawning grounds, American shad will utilize spawning habitat in proportion to its availability.

STUDY AREA

The Neuse River is formed by the confluence of the Eno and Flat rivers in the piedmont region of North Carolina and flows in a southeasterly direction through the coastal lowlands, discharging into Pamlico Sound, 430 km from its origin (Hawkins 1980; USGS 1995). Through the Piedmont, the Neuse River has a relatively high gradient, and substrates tend to be rocky (USGS 1995). As the river passes through the fall line into the coastal lowlands, the river widens and slows as the gradient lessens. Downstream of the fall line, substrate is dominated by sand and silt (USGS 1995).

The Neuse River resides entirely within North Carolina and drains approximately 14,500 km^2 of land, which is comprised of approximately 48% forest, 30% agriculture, 9% wetlands, 6% developed lands, and 5% water (Hawkins 1980; USGS 1995). Flow regimes in the Neuse River downstream of Raleigh, NC, are controlled by Falls Lake Dam (rkm 370), which was built in 1983 by the U.S. Army Corps of Engineers to create an impoundment for flood control, water supply, water quality, and recreational purposes.

SPECIES ACCOUNTS

Striped Bass

Striped bass are an iteroparous species that spawns in rivers along the Atlantic Coast between the St. Lawrence River, Canada, and the St. Johns River, Florida (Raney 1952; Scott and Scott 1988). Striped bass of many populations along the Atlantic Coast undergo coastal, nearshore migrations. However, many southern populations are different in that a large percentage of adults reside in the lower river or estuary throughout the winter as opposed to making coastal migrations common to more northerly populations (Raney 1952; Chapoton and Sykes 1961; Rulifson et al. 1982).

In the southeastern U.S., spawning occurs between 12 and 24^{o}C, although peak activity is between 18 and 21^{o}C (Hill et al. 1989). Striped bass spawn in areas from 0.3 to 6.1 meters in depth. Spawning migrations can be restricted to the tidally influenced freshwater zone, as in the Savanah River, or migrations can be quite extensive, reaching as far as 320 km up-river (Dudley et al. 1977; Hardy 1978).

Spawning activity normally begins at dusk. Typically, several males spawn with a single female, which often results in splashing at the surface. Striped bass spawn in moderate to swift currents, as egg survival is low if they are not suspended in the water column (Mansueti 1958; Albrecht 1964). Gametes are broadcast into the water column and the semi-buoyant fertilized eggs drift downstream, where they hatch in 29 to 80 hours depending on local water temperatures (Setzler et al. 1980). Very little is known about the movements of early life stage striped bass. However, in the South Atlantic, tidally influenced freshwater areas and estuaries act as important nursery grounds (Rulifson et al. 1982).

American Shad

Like striped bass, American shad are an anadromous species that use many of the rivers along the North American Atlantic Coast to spawn (Scott and Crossman 1973). American shad also make extensive latitudinal coastal migrations tracking ocean temperatures of 13 to 18^{o}C (Leggett 1973). Once river temperatures rise above 4^{o}C, American shad begin to enter their natal river in increasing numbers, until 13^{o}C, at which point movement into the rivers declines (Walburg and Nichols 1967; Leggett 1973). Spawning takes place in the mainstem of the river and in larger tributaries, and given access, they will ascend hundreds of kilometers to the headwaters to spawn (Stevenson 1899).

The reported habitat requirements of spawning American shad are broad and inconsistent among studies (Stier and Crance 1985). American shad have been found to spawn at a wide range of temperatures; however, spawning activity is greatest between 14 and 21^{o}C (Walburg and Nichols 1967). No consensus has been reached on the substrates American shad utilize, as they have been shown to spawn over various substrate types (Walburg 1960; Layzer 1974; Leggett 1976). However, it has been suggested that they prefer sand and gravel substrates with moderate velocities (Walburg and Nichols 1967; Beasley and Hightower 2000). Ross et al. (1993) found no correlation between spawning and water velocity and thus concluded that velocity may not be an important habitat requirement. This is not consistent with the conclusions by Walburg

(1960) that sufficient current is required to buoy eggs in the water column to maximize hatching success.

Spawning typically begins at dusk (Massman 1952) and often involves a group of individuals, presumably a single female with a group of males. Spawning is often accompanied by characteristic splashing or "fighting" at the surface (Leim 1925). Once the negatively buoyant, non-adhesive eggs have been broadcast into the water column, they sink and often become lodged in the substrate within a few meters (Carlson 1968). However, eggs that do not settle have been shown to drift as far as 6 km downstream (Marcy 1972).

Typically, fry emerge in 6 to 12 days in waters of 12 to 19^{o}C, but the incubation period is extremely dependent on water temperature (Walburg and Nichols 1967). Juvenile American shad generally remain in riverine or estuarine areas until the fall of their first year, then move offshore when temperatures fall below 15^{o}C (Walburg and Nichols 1967). In southern rivers, male and female American shad return to their natal rivers to spawn when they mature at 3-5 and 4-6 years, respectively (Sholar 1977; Fischer 1980; Hawkins 1980).

There is a strong positive relationship between the degree of iteroparity in American shad populations and the latitude of each spawning population. Hawkins (1980) assessed the degree of American shad interoparity in the Neuse River and reported estimates of 9 and 7%, for males and females respectively. In comparison, no American shad were found to spawn a second time in the St. Johns River, Florida. In the Connecticut River, upwards of 50% had spawned at least twice, and some individuals spawned as many as five times (Leggett and Carscadden 1978).

METHODS

Spawning Distribution

We used radio telemetry to track individuals throughout their spawning migration, and to address the hypothesis that dam removal will not affect the spatial distribution of spawning striped bass and American shad (Hypothesis 1). The maximum distances migrated by telemetered fish in this study were compared to those found by Beasley and Hightower (2000) to determine if there was a post-dam removal effect on migrational patterns.

Striped Bass

Striped bass were captured by electrofishing. To ensure that striped bass were sexually mature, we only implanted transmitters in males and females having total lengths greater than 500 and 550 mm respectively (Olsen and Rulifson 1992). Striped bass meeting length requirements were also required to weigh at least 1,400 g, so that the transmitter weight would not exceed 2% of that of the fish (Winter 1983). Transmitters were distributed evenly between the sexes.

Striped bass received one of two ATS (Advanced Telemetry Systems, Isanti, Minnesota) transmitter models, either model 6AA or 5902 (1/2AA). Each model 6AA radio transmitter had a unique frequency between 49.500 and 50.000 MHz. These transmitters had a duty cycle of 214 days on and 151 days off resulting in a maximized battery life of 520 days. These cylindrical transmitters measured 66 x 18 mm in size and weighed between 26.47 and 27.76 g. The model 5902 (1/2AA) transmitters had unique frequencies ranging from 41 to 42 MHz. They measured 17 x 40 mm in size and weighed approximately 17 g. They had a guaranteed life of 300 days having a 12-hour on, 12-hour off schedule. These transmitters were not operational during the second year of study.

Prior to implantation, fish total length and weight were measured. Radio transmitters were surgically implanted into the peritoneal cavity of the striped bass using a technique described in detail by Haesaker et al. (1996). Floy® internal anchor tags were inserted in each fish at the location from which scale samples were taken. Each tag had a unique identification number to identify it as a study fish if captured, ideally prompting its release.

In 1999, logistical difficulties delayed striped bass transmitter implantation, and transmitters were not implanted until 8 March to 14 April, which resulted in release locations at several sites between New Bern (rkm 75) and Kinston (rkm 135), NC. A total of 28 striped bass were implanted with radio tags during the 1999 field season, 14 of each sex. Difficulties in collecting female striped bass made it necessary to use 5 individuals that did not meet the 550 mm minimum length requirement (Table 1). However, their sexual maturity was confirmed visually through the incision at the time of implantation. In 2000, transmitters were inserted into 10 striped bass (5 males and 5 females) on 4 and 7 February, near New Bern, NC (rkm 75) (Table 2).

American Shad

American shad were captured either by electrofishing or by drifting a gill net. The drift net was 50 yards in length by 6 yards deep, with a stretch mesh size of 5¼ inches. No minimum size criteria were required as all fish entering the river were assumed to be sexually mature. A minimum weight requirement of 500 g was used to ensure that the transmitter weight would not exceed 2% of the fish weight (Winter 1983).

All transmitters implanted in American shad were ATS, standard model 10-28. Each had a unique frequency and was programmed to transmit continuously throughout the guaranteed lifespan of 90 days. Transmitters operated in either the 41 to 42 MHz or 49 and 49.500 MHz range. Cylindrical transmitters measured 45 x 13 mm and weighed between 8.40 and 8.93 g. Total length, weight, and scale samples were taken prior to the implantation. The transmitters were inserted into the stomachs after they were coated with glycerin to facilitate insertion and reduce the risk of esophageal injury. To minimize handling stress, fish were released immediately upon transmitter insertion.

In 1999, American shad were collected during the second week of April because of delays in obtaining transmitters. Transmitters were implanted at several sites between Spring Garden, NC (rkm 85), and Ferry Bridge Rd, Goldsboro, NC (rkm 239), 14 rkm above the former site of Quaker Neck Dam (Table 3). Twenty-five transmitters were implanted into American shad during the 1999 field season. Sex was not determined for American shad in 1999.

In 2000, all transmitters were implanted at Spring Garden on 4 and 5 March (Table 4). A total of 13 transmitters (7 females, 6 males) were implanted in American shad in 2000. American shad were considered male if we were able to express milt, and if no milt was expressed, the fish was presumed to be female.

Tracking

Two fixed, remote telemetry stations were used to track those American shad and striped bass transmitters at frequencies between 49 and 50 MHz. In 1999, telemetry stations were located near Goldsboro (rkm 224), 1 km downstream of the Quaker Neck Dam site, and at the Johnston County Water Treatment Facility (rkm 285) (Figure 1). In 2000, telemetry stations were located at Goldsboro (rkm 224) and near New Bern, NC (rkm 84). Each remote telemetry station was comprised of two Hy-Gain®, model 64DX, 4-element directional Yagi antennas, ATS model R2100 receiver, and an ATS model DCC II data logger. At each station, one antenna was angled downstream and the other upstream so that migrational direction could be determined by comparing signal strength between the two antennas.

We tracked actively by boat using Cushcraft®, CRS-4 and CRS-3 multidirectional antennas and ATS model R2100 receivers to monitor the movements of fish implanted with tags transmitting on all frequency ranges. Once the general location of a fish was determined, a paper clip was used as a weak antenna to establish the location within approximately 10 m. We then recorded frequency, location, date, time, and basic habitat variables, including water depth, salinity, air temperature, surface water temperature, and cover. Our tracking regime was not systematic. To maximize the number of relocations, tracking effort was concentrated on localities of where the bulk of our telemetered fish were located at any one time.

Data Analysis

We used ArcView® Geographic Information System software to illustrate the spatial distribution of striped bass and American shad throughout their spawning migration. Discharge data were obtained from U.S. Geological Survey gaging stations, and water temperature was recorded using Hobo® temperature loggers positioned at each remote telemetry station. Prior studies have shown that a great deal of the variation in migrational movement of striped bass and American shad can be explained by temperature and discharge (Leggett 1973; Carmichael et al. 1998).

Spawning season length could only be reliably assessed in 2000. In 1999, late transmitter implantation, and difficulties relocating fish made it difficult to establish when American shad and striped bass began and finished their spawning migrations. Because American shad were intercepted as they migrated upriver, the beginning of in-river migration was considered to be the day of transmitter implantation (3 March 2000). However, some American shad had most likely commenced their in-river migration prior to this time. American shad in the Neuse River are semelparous and do not out-migrate. Thus, the end of the spawning period was considered to occur the last day that we observed any spawning activity (7 June 2000). Striped bass spawning migration was considered to have started when the first telemetered fish was recorded moving upstream, past the lower most telemetry station (rkm 84) (15 March 2000). Striped bass spawning migration was considered over when the last out-migrating fish passed the lower most telemetry station (26 May 2000).

We used a two-sided, Mann-Whitney U test to compare maximum distances migrated between the sexes for both species. In addition, a one-tailed, Mann-Whitney U test was used to compare maximum distances migrated between pre- and post-dam removal periods. Although the Mann-Whitney U test does use distribution shape to test for differences between samples like the Kolmogrov-Smirnov test, it is more powerful when the user is only concerned with rank location and not distribution of the data (Sokal and Rohlf 1995).

Spawning Habitat Assessment

To test the null hypothesis that American shad used similar habitat in the pre- and post-dam removal periods (Hypothesis 2), we compared the utilized habitat data derived from this study with that of Beasley and Hightower (2000). Utilized habitat data by year were pooled within their respective periods (pre-dam and post-dam removal).

To address the null hypothesis that American shad used habitat in proportion to its availability on a microhabitat scale (Hypothesis 3), we compared the microhabitat used by spawning fish to the habitat available within a discrete spawning area. Microhabitat is defined as a "specific combination of habitat elements in the place occupied by an organism for a particular purpose" (Murphy and Willis 1996). For the purpose of this study the combination of habitats was substrate, depth and velocity and the place occupied is the specific point of an American shad spawning event.

Available Spawning Habitat

To quantify available habitat within an area that was used intensively by spawning American shad, we used a transect and point-intercept method (Hamilton and Bergersen 1984). Transect sampling intensity was based on mean river width (MRW) from 10 random width measurements within the identified spawning grounds (Simonson et al. 1994). The first transect was selected randomly, and following transects were spaced 0.5 mean river widths apart. Mean river width was 49 meters, and transects were completed every 24.5 meters (MRW/2) throughout the 600-m reach in which spawning was observed. This sampling effort is greater than what is recommended for a river of this size (Simonson et al. 1994), but as we are examining habitat utilization on a microhabitat scale, we believe that this sampling intensity was reasonable.

Transects were located perpendicular to the flow. On each transect, depth, current velocity and substrate were measured at 0.25 m from the bank, then every 2 m thereafter, and again at 0.25 meters from the far bank. Depth was measured to the nearest centimeter with a sounding pole. Surface current velocity was measured with a Model 201D Marsh McBirney® meter. Velocities were measured by orienting the meter parallel to the current. Reverse flows registered as negative velocities and were considered to be valid observations that represented eddying currents. A sounding pole was used to determine substrate type, and at each sampling point dominant and co-dominant substrates were identified. Substrates were categorized based on a modified Wentworth Particle Size scale (Wentworth 1922) (Table 5).

Used Spawning Habitat

Throughout the spawning periods of both species, night searches for spawning activity were made by drifting downriver and listening for the characteristic splashing or “fight” that indicates a spawning event (Leim 1925). Striped bass fights are protracted and boisterous, whereas American shad fights are relatively small in comparison. Thus, it is possible to audibly identify the species responsible for the spawning activity. A spotlight aided in precise location of spawning activity and when possible was used to visually confirm species' identification. Night searches for spawning activity were not systematic. Searches were designed to find spawning activity and identify possible spawning grounds throughout the entire river. The location of searching during the spawning season was often directed by the location of telemetered fish. Due to difficulties navigating the river at night, our searches were restricted to within approximately 10 rkm of a river access point. Therefore, we may not conclude that we located all the principle spawning grounds in the Neuse River.

When a spawning event was observed, depth, velocity, and substrate were measured at the exact location of spawning using the methods described above. In addition, water temperature, air temperature, and dissolved oxygen were measured using a YSI Model 55 dissolved oxygen meter. These three variables are susceptible to diel fluctuations, and available and utilized habitat data were collected on different days and at varying times within the day. Therefore, those variables were not included in the analyses.

Data Analysis

A Kolmogorov-Smirnov (K-S) two-sample test was used to test for differences between available and utilized habitat. Unlike independent samples tests including t-tests and the Mann-Whitney test, which only test for differences in location of the two samples, the K-S test is sensitive to differences in location, skewness and kurtosis (Sokal and Rohlf 1995).

In addition, a K-S test was used to test for differences between utilized habitat in the pre- and post-dam removal periods (pooled). Depth and velocity data from both periods were tested against each other directly, as the methods of collection were identical. However, substrates in the pre- and post- dam removal studies were collected using different techniques. The pre-dam study utilized a hardness scale from 1 to 6 in which clay was assigned a rank of 1, silt – 2, sand – 3, gravel – 4 , cobble – 5, and bedrock – 6 (Beasley and Hightower 2000). The percent substrate in each category was multiplied by its rank value, summed across the sample and divided by 100, which gave an average substrate hardness value from 1 through 6. For substrates to be compared between studies, our 6 substrate categories, silt/clay through boulder were transformed into ordinal classes, 1 through 6 respectively.

RESULTS

Discharge

Flows during much of the spring 1999 field season were below the median historical level. Except for a brief period of higher flow around April 1 and May 1, flows at the Goldsboro USGS gaging station were similar to the 25th percentile of historical discharge (Figure 2). Discharge during 2000 was generally more similar to the median historical discharge then they were in 1999; only for brief periods at the beginning and end of the spawning season was discharge below the 25th percentile of historical discharge (Figure 2). The Neuse River is susceptible to rapid fluctuations in flow, and downstream of rkm 370, discharge is controlled in part by releases from Falls Lake Dam.

As anadromous fish move upriver, the magnitude of the fluctuations in relation to base flow is amplified, as there are fewer inputs from tributaries to buffer changes in flow.

Water Temperature

Water temperature at the Goldsboro telemetry/logging station during the 1999 spawning season for American shad and striped bass ranged from 12.8 - 32.3^{o}C, and the median was 19.9^{o}C (Figure 3). In 2000, water temperature ranged from 10.92 - 26.9^{o}C, and the median was 18.1^{o}C. The greater range of temperatures in 1999 was most likely caused by the uncharacteristically low discharge (Figures 2-3).

American Shad

Of the 25 American shad implanted with transmitters, 9 were never relocated and it was assumed that they abandoned migration. Of the remaining 16 fish, 1 died as a result of handling and transmitter insertion and 4 others displayed signs of post-implantation “fallback” and ultimately abandoned migration. Fallback occurs when a migrating fish moves downriver after release due to the stresses of handling and transmitter implantation (Moser and Ross 1993). These fish were omitted from subsequent analyses (Table 3).

In 1999, 9 of 11 telemetered American shad providing useful data migrated upstream of the former Quaker Neck Dam site. All the telemetered American shad halted their migration within 16 rkm upriver of the former dam site (rkm 225), well below the next artificial or natural impediment (Figure 4). The maximum distance migrated by an American shad was 241 rkm, and the average maximum distance migrated was 235 rkm.

In 1999, we identified a 600-meter reach at rkm 239 near Ferry Bridge Rd., 14 rkm upstream of the Quaker Neck Dam site, that had an extremely high concentration of American shad spawning activity, including but not limited to telemetered fish. Telemetered American shad were located on the spawning grounds by mid-April. We observed spawning events between 25 April and 18 June between the times of 2020 and 2221. Water temperatures during spawning events ranged from 15.2 - 28.2 ^{o}C (median = 23.4 ^{o}C). After spawning, most American shad died very near their spawning grounds, as determined by repeated location at the same point in the river (Figure 5).

Distributions of substrates, current velocities, and depth at American shad spawning sites in 1999 differed significantly from available habitat within the primary spawning grounds (Table 6). American shad spawned over larger substrates such as coarse gravel, cobble and boulder than those available (Figure 6-7). The habitat in this 600-m reach was considerably different from that of nearby reaches, as it contained sections of gravel, cobble, and boulder substrate (Figure 7), whereas neighboring reaches were comprised almost completely of sand and silt. American shad spawned almost exclusively at velocities ranging from 0.20 to 0.60 m/s (Figure 8). American shad tended not to use habitat that had current velocities outside that range. Spawning was observed most frequently at depths of 50 to 125 cm and avoided depths less than 50 cm (Figures 9-10).

In 2000, all transmitters were implanted at Spring Garden, NC (rkm 85), during the first week of March. An angler caught one American shad early in the spawning season, and its transmitter (frequency 49.541) was re-inserted on 21 March. Data collected from the first telemetered American shad were not included in the analyses due to its short time at large. One female American shad abandoned migration after being relocated twice.

The average distance migrated by American shad in 2000 was 215 rkm (Figure 11), 26 rkm less than the previous year. The maximum distance migrated was 282 rkm. Telemetered American shad did not congregate in any one area but generally reached their respective spawning grounds by mid-March (Figure 5). As in 1999, there was little attempt at out-migration. There was no difference between the distances migrated by male and female American shad during the 2000 spawning season ($p = 0.60$).

In 2000, even though our telemetered fish did not congregate in one specific area, we verified through night searches that there was a large amount of spawning activity occurring in the same 600-meter reach of river as in 1999. Our spawning searches did not reveal any other spawning areas that had nearly as much activity as this reach. Because the high concentration of American shad in this area seemed to indicate that this section of river provided important spawning habitat, we repeated our spawning habitat sampling at this site. We observed spawning events between 15 April and 7 June, between the times of 2004 and 2105. The water temperatures at which we observed spawning ranged from 14.9 – 29.6^{o}C (median = 22.5^{o}C).

There were significant differences between used and available spawning habitat of American shad in terms of substrate and depth in 2000 (Table 6). American shad used silt/clay, cobble, and boulder sites in greater frequency than their availability (Figures 6 and 12). Surface velocities at spawning sites were not significantly different from the distribution of available velocities (Figure 8). American shad used depths that were significantly greater than those available (Figures 9 and 13). In 1999 and 2000, American shad consistently spawned in the same areas within the spawning grounds (Figure 7 and 12).

It should be noted that all available habitat variables were significantly correlated, which creates difficulties when attempting to discern if American shad were using the Ferry Bridge Rd. spawning area as a result of a single habitat characteristic or a suite of habitat variables.

Striped Bass

Due to the cumulative stresses of migration and invasive surgery, there were five mortalities attributed to surgery and handling. An additional 9 individuals displayed fallback behavior that ultimately lead to abandonment of migration (Table 1). As a result, 14 telemetered striped bass provided useful migration data, with 8 of the 14 migrating above the former site of Quaker Neck Dam (Figure 14). The average maximum distance migrated was 224 rkm, and the furthest distance migrated by an individual was 302 rkm, near Smithfield. Male and female striped bass did not migrate significantly different distances in 1999 ($p = 0.66$). However, the sample size was extremely small as 12 of 14 telemetered females abandoned migration. Relocations of individuals were dispersed throughout much of the river, with no obvious concentration of fish that might denote a spawning ground location (Figure 14). Telemetered striped bass moved rapidly up-river, and most had reached the maximum extent of their migration by the third week in April (Figure 15).

Beginning 16 April 1999, there was an aggregation of 11 radio telemetered striped bass between rkm 205 and 225 (Figure 15); however, at this time discharge declined substantially (Figure 2), and there was little attempt made to migrate beyond this area. Daytime-high water temperatures at the Goldsboro station had reached 21.2 ^{o}C on 10 April 1999. This is the temperature threshold when striped bass might normally begin out-migration (Carmichael et al. 1998), although by April 16 water temperatures had cooled to 19.3 ^{o}C. On 3 May 1999, it appeared that 2 of the striped bass attempted to move upriver (rkm 254 and 262) coinciding with an increase in discharge measured at the USGS gaging station near Goldsboro from 25.2 m^3/s to 58.3 m^3/s beginning on 30 April 1999. However, prior to this increase in discharge, water temperatures had been consistently reaching 21 ^{o}C. On 9 May 1999, 2 additional fish moved to rkm 240 (Figure 15), most likely in response to a second increase in discharge that peaked on 7 May 1999 at 76.5 m^3/s (Figure 2).

The mean distance migrated during the 2000 spawning season was 251 rkm, 26 rkm above the former Quaker Neck Dam site, and the maximum distance migrated was 309 rkm (Figure 16). On average, striped bass migrated 32 rkm farther in 2000 than they did in 1999. Striped bass began up-river migrations from 26 March to 16 April. Ascension up-river was rapid, and telemetered striped bass may have been on the spawning grounds from 7 April to 7 May 2000. In 2000, male and female striped bass migrated a mean maximum distance of 307 and 206 rkm, respectively. The difference was marginally significant ($p = 0.06$).

In 2000, 5 of 9 telemetered striped bass were aggregated on 5 May 2000 between rkms 298 and 316. This aggregation of fish could indicate a potential spawning area. However, on 1 May 2000, 2 of the 5 striped bass were located 1 and 6 rkm upstream from where they were located on 5 May, suggesting that the 5 fish located on 5 May 2000 had already begun out-migration. On 23 April 2000, discharge at the Clayton USGS gaging station was as high as 85.0 m^3/s. Telemetered striped bass may have taken advantage of these high discharges and migrated all the way to Milburnie Dam (rkm 341). However, this is speculation only and not directly supported by the telemetry data. Between 23 April and 5 May 2000 discharge measured at a USGS gaging station located at Clayton (rkm 315) decreased from 85.0 to 25.3 m^3/s. This substantial reduction in discharge may have contributed to the rapid out-migration of striped bass after 5 May. In addition, on 5 May 2000, daytime-high water temperature at Goldsboro had reached 20.1 ^oC, which corresponds with temperatures known to initiate striped bass out-migration in the Roanoke River (Carmichael et al. 1998).

Although extensive spawning searches were made in areas where telemetered striped bass were concentrated, no striped bass spawning activity was witnessed. In 1999 and 2000 spawning may have coincided with brief peaks in discharge, thus resulting in a short period in which spawning could be observed.

Pre- and Post-Dam Removal Comparison

There was no consistent trend in the maximum distance migrated by telemetered American shad and striped bass between pre- and post-dam removal studies (Table 7). In 1999, the mean maximum distance American shad migrated was significantly greater than that of the pre-dam removal period, but in 2000 there was no significant difference between maximum distances migrated. The mean maximum distances migrated by telemetered striped bass and American shad after the dam removal were consistently greater than before the dam was removed; however, the differences were not statistically significant (Table 7).

Spawning habitat used by American shad was significantly different for all variables between pre- and post-dam removal periods (Table 8). The mean depth that spawning American shad used before dam removal was significantly deeper than after dam removal. Before dam removal, American shad used surface velocities that were significantly slower than after dam removal. Substrates used prior to dam removal were significantly larger than those utilized after the dam was removed.

DISCUSSION

Because discharge and water temperature are important factors controlling striped bass migration (Manooch and Rulifson 1989; Carmichael et al. 1998), we surmise that low discharges and high temperatures in 1999 played a considerable role in the failure of striped bass to migrate as far as they did in 2000. In 1999, low discharges meant that many rapids were exposed at the fall line (rkm 296), and it is likely that the striped bass may be unable to navigate this obstruction.

In 1999, 10 telemetered American shad migrated into habitat made available by dam removal; however, they spawned well downstream of the next upstream obstruction to migration (Milburnie Dam). After transmitter insertion, American shad exhibited little movement, upriver or downriver. We were unaware at the time that a number of the American shad that we telemetered were already near their spawning grounds, thus biasing the maximum distance migrated of our sample.

Contrary to our expectations, American shad did not migrate farther in the 2000 spawning season in response to greater seasonal discharge. Only 2 of the 12 telemetered American shad migrated beyond the Quaker Neck Dam site. In 1999, the data show that telemetered American shad migrated significantly farther than they did before the dam was removed. Because many of the transmitters in 1999 were implanted above Quaker Neck Dam, these data are biased enough that they cannot be used when comparing pre- and post-dam removal migrations of American shad. In 2000, American shad did not migrate significantly farther than they did before the dam was removed. Due to earlier implantation of transmitters in 2000, the American shad telemetry data were considerable more reliable in that year. Therefore, we only used telemetry data in 2000 to determine if there was a dam removal effect on American shad migration. As such, we do not reject the null hypothesis that the spatial distributions of spawning American shad are not different between pre- and post-dam removal periods. Even though telemetered American shad did not migrate significantly farther than the former site of Quaker Neck Dam, there is evidence that American shad are migrating to Milburnie Dam. In 1998, before the dam was removed, sluice gates lifted from Quaker Neck Dam allowed American shad to pass over the dam and (Brad Hammers NCWRC personal communication) and they were collected in large numbers at the base of Milburnie Dam. American shad were also found immediately below Milburnie Dam in large numbers during the 2000 spawning season (Christian Waters NCWRC personal communication). It appears that even though American shad made use of the restored habitat immediately downstream of Milburnie Dam, our telemetry methods were not sufficient to detect

American shad migration that far upriver. A larger sample size or perhaps a less biased technique of evaluating migration may have yielded more thorough results.

Telemetered striped bass and American shad in the 1999 field season exhibited a strong fallback response after transmitter implantation. In addition to handling and surgery stresses (Carmichael et al. 1998), the magnitude of fallback was probably exacerbated by the late date of transmitter insertion, by which time many of the fish had already completed a portion of their in-river spawning migration. In 2000, striped bass were given a greater time to recuperate after surgery, and transmitters were implanted in American shad earlier in the spawning season when water temperatures were cooler.

During night searches for spawning activity, we located no other spawning sites that approached the degree of spawning intensity at the Ferry Bridge Rd. spawning area. The habitat in this 600-m reach of river is extremely heterogeneous, providing a diverse habitat mosaic from which American shad could use specific sites in which to spawn. The reach had slow moving sandy areas analogous to the lower section of the river, but also faster, rocky sections similar to the upper reaches of the river. This site may be favored because this reach represents an isolated patch of habitat typical of that normally only found upstream of the fall-line where substrates are much more rocky (USGS 1995). Immediately upstream and downstream of the Ferry Bridge Rd. spawning grounds, the substrate is dominated by sand and silt/clay, habitat typically not used by spawning American shad.

This site perhaps offers the ‘optimal’ habitat characteristics for the least amount of energy expended to reach it from the river mouth. American shad in the St. Johns River, Florida, expended 70% of their energy reserves migrating to the spawning grounds

(Glebe and Leggett 1981a). From spawning checks on scales, Hawkins (1980) estimated that 9% and 7% of male and female American shad in the Neuse River were iteroparous, respectively. Thus, the extent of up-river migration might be a trade-off between finding optimal spawning habitat and the probability of surviving to reproduce another year. Glebe and Leggett (1981b) determined that intra-population, post-reproductive survival is partially controlled by energy constraints. If American shad populations return to near historic levels, density-dependent factors may induce more American shad to lengthen their migration into less densely occupied, but more energetically costly sites.

The identified spawning grounds near Ferry Bridge Rd. may currently be the main spawning area for American shad in the Neuse River, as considerable numbers of American shad spawned at this site in both years of the post-dam removal study. In addition, anecdotal evidence provided by a landowner with property adjacent to the spawning area suggests that American shad have historically spawned in great numbers at this location (Ron Steilles personal communication).

In 1999, the majority of the telemetered American shad were located at the Ferry Bridge Rd. spawning grounds, but this was most likely a result of having the transmitters implanted in the vicinity. In discord with the above observations, no American shad telemetered in 2000 were located in this area, indicating that telemetry data might be giving a biased description of where the spawning grounds are located. A less likely explanation would be that the lack of telemetered American shad at the Ferry Bridge Rd. spawning area in 2000 may indicate that the contribution of this 600-m reach to total reproduction may be small, relative to reproduction in the entire river. In 2000, upriver shad migrations were direct and rapid, suggesting that transmitters were not influencing migration. An intensive mark-recapture study would be useful in deriving a better estimate of the relative contribution of the Ferry Bridge Rd. spawning grounds to American shad spawning habitat.

We found that American shad used significantly different spawning habitat in the pre- and post- dam removal periods. This difference, although small and not biologically significan was expected, as the available habitat above the dam is significantly shallower and faster than the habitat below the dam (Beasley and Hightower 2000). Despite the statistical significance of the differences in habitat between the pre- and post-dam removal periods, American shad used remarkably similar mean habitat before and after dam removal. Beasley and Hightower (2000) found that prior to the removal of Quaker Neck Dam, American shad used mean water velocities of 0.34 m/s. This corresponds closely to mean velocities of 0.37 m/s observed in the current study. In addition, Beasley and Hightower (2000) found a mean spawning depth of 1.35 m, which is very similar to 1.16 m as determined in the current study. In the pre-dam removal period, American shad selected shallow spawning sites relative to random habitat samples from the lower river, and in the post-dam removal period, American shad selected deep spawning sites relative to the habitats available at the Ferry Bridge Rd. spawning area, yet the mean spawning depths are quite similar. This gives further support to the hypothesis that American shad are selecting similar pre- and post-dam removal habitat. There was also correspondence in the substrates American shad selected in these two studies. Both studies found that American shad used larger substrates in greater frequency than their availability. Some of the most compelling evidence of habitat selection was the strong inter-year utilization of very specific sites within the spawning grounds near Ferry Bridge

Rd, Goldsboro. Layzer (1974) also noted that American shad used discrete spawning sites in the Connecticut River. These observations contradict the belief that spawning American shad have few habitat requirements (Stier and Crance 1985; Ross et al. 1993). The close correspondence between habitat used by American shad before and after dam removal implies that the removal of Quaker Neck Dam did not dramatically influence the type of habitat that American shad used, but rather the amount of it available to them.

To increase evolutionary fitness it makes sense that American shad time their migration and use habitat that would maximize the survival of their progeny. Because eggs are not motile and receive no parental care, they are completely dependent on their environment for survival during their 4-6 day incubation period. Thus, it might be expected that American shad be genetically predisposed to select habitat to maximize egg survival. However, there is little concurrence in the literature on the fate of fertilized American shad eggs. Some authors suggest that the negatively buoyant non-adhesive eggs (Mackenzie et al. 1985) require currents to keep them suspended in the water column and are able to drift up to 6.7 km downriver (Marcy 1972; Sholar 1977), whereas others suggest that eggs may settle and become lodged on the bottom a short distance from where they were spawned (Moser et al. 1998). In both years of this study, American shad spawned in considerable numbers at a very specific and unique site that was typified by coarse substrates and shallow water, compared to the surrounding river, where substrates were dominated by sand and the water was deeper. One might question the advantage of having such specific spawning habitat requirements if the eggs are going to drift out of the habitat over which the adults spawned. However, if negatively buoyant, fertilized eggs settle out of the water column into a gravel/cobble substrate, they will become lodged (Layzer 1974; Moser et al. 1998) and it is critical that there be sufficient dissolved oxygen concentrations at the substrate-water interface. Marcy (1976) found no American shad eggs below dissolved oxygen concentrations of 5 mg/L. Bradford et al. (1966) reported 50% egg mortality at dissolved oxygen concentrations between 2.9 and 2.5 mg/L for various Atlantic coast stocks of American shad. By using coarser substrates such as gravel and boulder and avoiding silt and sand substrates, egg aeration will be promoted by forced convection from subsurface water movement (O'Brien et al. 1978), thereby potentially improving hatching success. In addition, the large gravel and cobble substrates could act as refugia for egg and pro-larvae stages, thereby reducing predator-related mortality (Layzer 1974). Eggs and prolarvae subject to currents (Ross et al. 1993) are likely to be much more vulnerable to predation drifting across a sandy substrate.

MANAGEMENT IMPLICATIONS

In many systems, discharge is a key component determining spawning success of anadromous fishes. For example, in the Connecticut River, American shad year class strength is controlled in part by river flow and temperature. May and June discharges explained 80-87% of recruitment variability in year-class strength in the Connecticut River between 1966 and 1980 (Crecco and Savoy 1987). The recognition of minimum flow requirements for anadromous fishes in the Neuse River could be applied to the revision of Falls Lake Dam release guidelines. If spring discharge could be modified to better meet the spawning requirements of anadromous fishes, they may be able to take full advantage of the restored habitat made available through dam removal.

In the Neuse River, adequate flows are most critical to migrating striped bass and American shad when they cross the fall-line (rkm 296). At the fall-line, waters become quite shallow, and if flows are low, numerous rapids may impede their up-river migration. Discharges up to 50 m^3/s appeared to hinder striped bass migration upriver of the fall-line. Therefore, a minimum discharge of 75 m^3/s is recommended to ensure that striped bass are able to pass over the fall-line. Given an upriver migration rate of 20 km/day for striped bass, (approximate rate based on 2000 data) the projected time of arrival at the fall-line would be 15 days after entry. The first striped bass might be expected to arrive at the fall-line by the end of March. In 2000, striped bass began out-migrating the first week of May. In the Neuse River, American shad began in-river migrations approximately the first week of March. Assuming an approximate up-river migration rate of 17 km/day (as found in this study), American shad could be expected to reach the fall-line by the middle of March. Therefore, to ensure that striped bass and American shad had ample opportunity to take advantage of the habitat restored by the removal of Quaker Neck Dam, a minimum discharge of 75 m^3/s beginning the 3rd week of Marc, through the entire month of April is recommended.

The results provided by this study may aid in the development of priorities for dam removal and fish passage projects along the eastern seaboard. Specifically, the conclusions from this project will yield information that will permit testing and refinement of spawning Habitat Suitability Index (HSI) Models for American shad. Currently the HSI for spawning American shad only incorporates temperature and velocity (Stier and Crance 1985). Stier and Crance (1985) report an optimal temperature range for spawning fish between 12.7 – 21.1^{o}C. In the Neuse River, we observed spawning at temperatures from 14.9 – 29.6^{o}C. Some spawning activity may have gone unobserved early in the season, and therefore a low optimal temperature of 12.7^{o}C may be reasonable for the Neuse River. Stier and Crance (1985) report that temperatures of 26.7^{o}C are not suitable to spawning American shad. However, we routinely observed spawning at temperatures as high as 28^{o}C. The upper bound of suitable spawning temperatures may need to be re-evaluated. This is especially true for rivers in the southeast, where water temperatures above 21^{o}C can occur quite early in the spawning season. In this study, 21^{o}C was first reached on 10 April and 7 May in 1999 and 2000 respectively. The HSI recommends that optimal velocities for spawning American shad range between 0.30 and 0.91 m/s. We observed spawning between velocities of 0.02 and 1.05 m/s. However, the majority of spawning events occurred between 0.10 and 0.60 m/s, which does not differ substantially than from that suggested by Stier and Crance (1985). The greatest discrepancy between the habitat used by spawning American shad in this study, and that reported as suitable by Stier and Crance (1985) is in respect to substrate. Although acknowledging that American shad eggs may be prone to suffocation if spawned over silt/clay substrates, they excluded substrate as a habitat variable from the HSI. In this study, American shad were predisposed to spawning over coarse substrates on both macro and microhabitat scales. Perhaps, when the American shad HSI Model is next reviewed, the importance of substrate will be given greater consideration.

Habitat restoration is a critical facet of fisheries enhancement that must be considered when attempting to restore, or in some cases re-introduce, anadromous fish populations that have been lost or damaged as a result of dam construction. Dam removal or the advancement in design of fish lifts and ladders can radically improve anadromous fish passage to previously inaccessible habitat (Hill et al. 1987; Richardson, and Minkkinen 1995).

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Table 1. Striped bass transmitter implantation and summary relocation data for the 1999 spawning season.

Transmitter Frequency (MHz)	Capture Date	Total Length (mm)	Mass (g)	Sex	Number of Relocations	Implantion Rkm	Maximum Rkm Migrated	Comments
40.922	3/8/99	509	1650	male	1	79	214	
40.910	3/18/99	519	1600	female	2	80	208	
40.930	3/18/99	617	2400	female	0	80	-	[*]abandoned
40.120	3/23/99	505	1550	male	4	80	240	
40.150	3/29/99	527	1725	male	2	80	214	
40.800	3/29/99	527	1500	male	2	78	253	
40.811	3/29/99	601	2600	male	4	80	224	
40.992	3/29/99	520	1700	male	0	79	-	abandoned
40.110	3/30/99	506	1450	male	2	97	243	
40.982	3/30/99	537	1625	female	0	97	-	abandoned
49.711	3/30/99	607	2600	male	6	98	302	
49.721	3/30/99	594	2600	male	5	98	199	
40.860	4/6/99	545	1650	female	2	99	-	[†]mortality
40.970	4/6/99	697	4150	female	1	97	-	abandoned
49.621	4/6/99	681	3875	male	5	99	261	
49.631	4/6/99	703	4300	male	6	97	214	
49.641	4/6/99	565	2000	male	4	97	-	mortality
49.692	4/6/99	662	3450	male	2	99	224	
40.950	4/7/99	540	1775	female	2	93	-	abandoned
49.601	4/7/99	515	1725	male	2	92	117	
49.591	4/12/99	566	2175	female	1	216	-	abandoned
49.651	4/12/99	535	1525	female	9	216	-	mortality
49.671	4/12/99	626	2450	female	8	218	-	mortality
49.681	4/12/99	573	2175	female	1	216	-	abandoned
49.702	4/12/99	590	2725	female	3	216	-	mortality
49.731	4/12/99	584	1850	female	1	216	-	abandoned
49.611	4/13/99	658	3200	female	2	225	-	abandoned
49.661	4/13/99	590	1925	female	2	229	235	

[*] Abandoned - refers to a fish that exhibited "fallback" behavior and withdrew from the river or was not relocated after transmitter insertion and thus it was assumed to have abandoned migration.

[†] Mortality - refers to a fish that was confirmed dead immediately after transmitter insertion.

Table 2. Striped bass transmitter implantation and summary relocation data for the 2000 spawning season.

Transmitter Frequency (MHz)	Capture Date	Total Length (mm)	Mass (g)	Sex	Number of Relocations	Implantion Rkm	Maximum Rkm Migrated	Comments
49.751	2/4/00	842	7950	Female	6	74	268	
49.761	2/5/00	737	4450	Female	5	74	305	
49.771	2/6/00	643	3300	Male	8	75	309	
49.781	2/7/00	572	1850	Female	7	74	101	
49.791	2/8/00	569	2250	Female	7	74	272	
49.741	7/4/00	556	2025	Female	5	75	84	
49.801	7/5/00	514	1550	Male	14	74	316	
49.810	7/6/00	510	1500	Male	11	74	303	
49.821	7/7/00	504	1450	Male	10	75	299	
49.830	7/8/00	500	1400	Male	0	74	-	*abandoned

* Abandoned - refers to a fish that exhibited "fallback" behavior and withdrew from the river or was not relocated after transmitter insertion and it was assumed to have abandoned migration.

Table 3. American shad transmitter implantation and summary relocation data for the 1999 spawning season.

Transmitter Frequency (MHz)	Capture Date	Total Length (mm)	Mass (g)	Number of Relocations	Implantation Rkm	Maximum Rkm Migrated	Comments
41.180	4/8/99	476	1050	0	150	-	*abandoned
41.360	4/8/99	502	1300	0	150	-	abandoned
41.230	4/9/99	512	1650	0	85	-	abandoned
41.260	4/9/99	504	1600	0	85	-	abandoned
41.290	4/9/99	524	1550	4	85	218	
41.210	4/12/99	439	850	1	214	-	abandoned
41.220	4/12/99	502	1200	0	211	-	abandoned
41.240	4/12/99	454	925	3	213	239	
41.300	4/12/99	394	675	0	214	-	abandoned
41.310	4/12/99	473	1075	5	213	217	
41.320	4/12/99	494	1250	0	214	-	abandoned
41.330	4/12/99	521	1450	0	214	-	abandoned
41.370	4/12/99	484	1100	1	217	-	abandoned
49.340	4/13/99	494	1100	6	239	239	
49.371	4/13/99	478	1175	8	239	239	
49.400	4/13/99	466	1050	7	239	240	
49.411	4/13/99	506	1050	8	239	239	
49.431	4/13/99	434	675	0	239	-	abandoned
49.441	4/13/99	459	825	5	239	240	
49.460	4/13/99	474	675	7	239	-	abandoned
49.491	4/13/99	480	1150	5	239	241	
49.520	4/13/99	479	1100	2	239	-	abandoned
49.550	4/13/99	488	900	2	239	239	
49.571	4/13/99	504	1100	6	239	-	†mortality
49.581	4/13/99	478	1025	5	239	239	

* Abandoned - refers to a fish that exhibited "fallback" behavior and withdrew from the river or was not relocated after transmitter insertion and it was assumed to have abandoned migration.

† Mortality - refers to a fish that was confirmed dead immediately after transmitter insertion.

Table 4. American shad transmitter implantation and summary relocation data for the 2000 spawning season.

Transmitter Frequency (MHz)	Capture Date	Total Length (mm)	Mass (g)	Sex	Number of Relocations	Implantation Rkm	Maximum Rkm Migrated	Comments
49.351	3/5/00	471	900	Female	2	85	-	*abandoned
49.360	3/4/00	509	1550	Female	16	85	214	
49.381	3/5/00	526	1800	Female	9	85	159	
49.390	3/5/00	521	1800	Female	4	85	282	
49.421	3/4/00	496	1540	Female	9	85	224	
49.451	3/4/00	539	2050	Female	4	85	163	
49.471	3/4/00	478	1100	Male	17	85	243	
49.481	3/5/00	472	1150	Male	15	85	224	
49.501	3/4/00	448	1200	Male	3	85	217	
49.511	3/4/00	502	1450	Male	16	85	235	
49.531	3/4/00	472	1400	Male	3	85	171	
49.541	3/21/00	482	1350	Male	8	85	220	
49.561	3/4/00	505	1750	Female	12	85	224	

* Abandoned - refers to a fish that exhibited "fallback" behavior and withdrew from the river or was not relocated after transmitter insertion and it was assumed to have abandoned migration.

Table 5. Substrate categories based on a modified Wentworth Particle Size scale.

Particle Category	Size Class (mm)
Silt/Clay	<0.62
Sand	0.62 – 2.0
Fine Gravel	2 –16
Coarse Gravel	16 – 64
Cobble	64 – 250
Boulder	250 – 4000
Bedrock	> 4000

Table 6. Means ± standard errors for depth, and water velocity during the 1999 and 2000 field seasons at randomly selected sites within the primary spawning grounds (available) and sites where American shad spawned (used). P-value from the Kolmogorov-Smirnov two-sample tests for each habitat variable are also presented.

	Depth (cm)			Velocity (m/s)			Substrate
	Available	Used	p-value	Available	Used	*p* -value	p-value
1999	71.5 ± 1.54	100.7 ± 3.91	< 0.001	0.26 ± 0.01	0.39 ± 0.01	< 0.001	< 0.001
2000	84.3 ± 1.46	132.2 ± 4.31	< 0.001	0.38 ± 0.01	0.36 ± 0.02	> 0.05	< 0.001

*Means were not presented for substrate as the data are ordinal.

Table 7. Means ± standard errors of maximum distances migrated by striped bass and American shad in the pre- and post dam-removal periods. The p-values from the Mann-Whitney U test comparing maximum migration distances between pre- and post-dam removal periods are presented. The 1999 American shad data are not presented as a result of bias.

	Mean ± SE	N	U	p-value
*American shad (96-97)	215 ± 3.8	10		
American shad (2000)	222 ± 10.2	12	58	0.89
*Striped bass (96-97)	215 ± 13.1	15		
Striped bass - 1999	224 ± 10.9	14	93	0.58
Striped bass - 2000	250 ± 30.4	9	36	0.06

*1996 and 1997 data are from Beasley and Hightower (2000).

Table 8. Means ± standard errors of substrates, depths, and velocities used by spawning American shad in the pre- and post-dam removal periods. The p-values from the Kolmogorov-Smirnov test comparing used American shad spawning habitat pre- and post-dam removal periods are also presented.

	Pre-dam		Post-dam		p-value
	Mean	N	Mean	N	
*Substrate	-	91	-	261	<0.001
Depth (cm)	135 ± 4.08	91	116 ± 3.06	261	<0.001
Velocity (m/s)	0.34 ± 0.01	91	0.37 ± 0.01	260	<0.025

*Means were not presented for substrate as the data are ordinal.

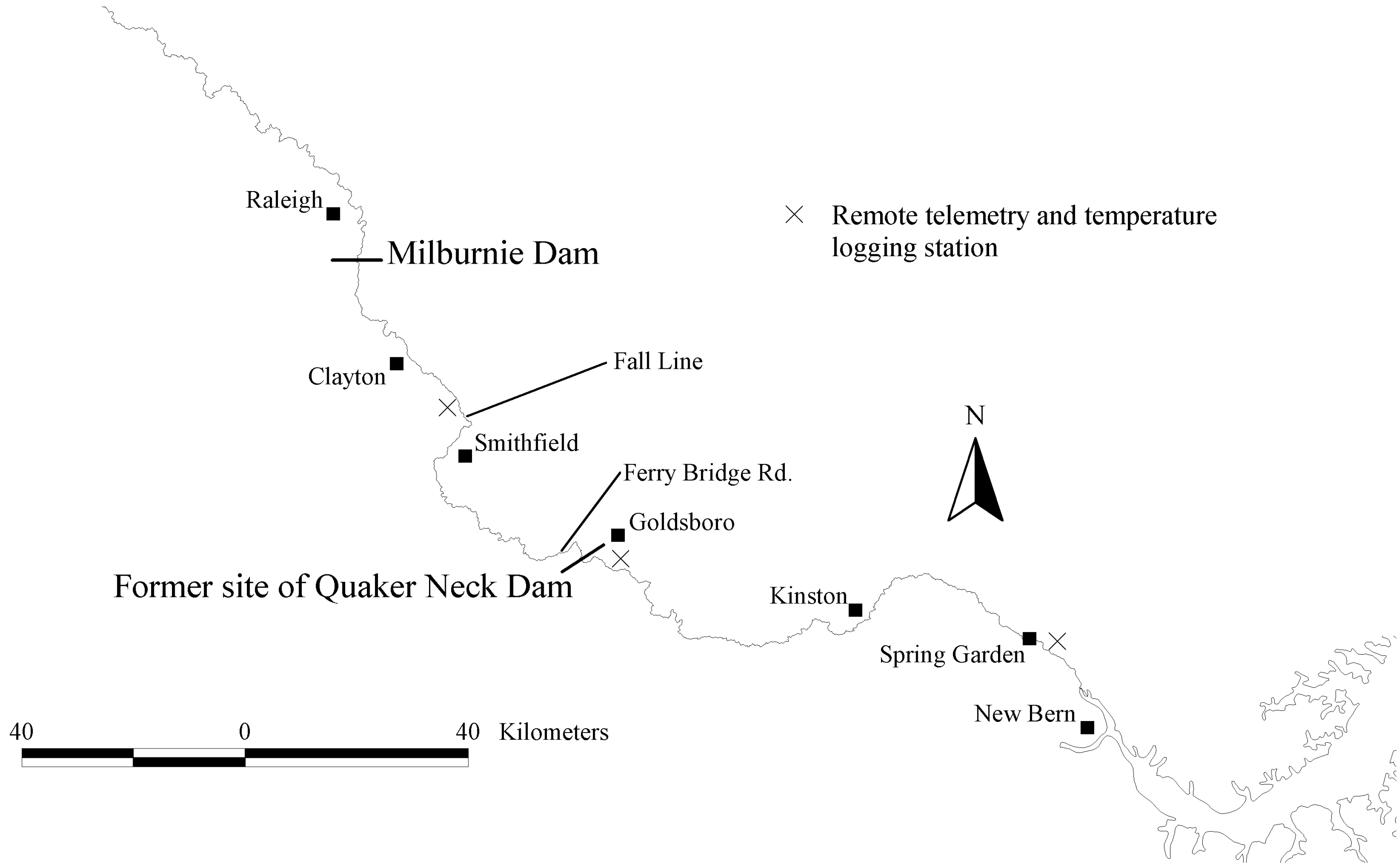

Figure 1. The Neuse River, North Carolina, and locations of the Quaker Neck Dam site, Milburnie Dam, and remote telemetry and temperature logging stations. In 1999, stations were located near Smithfield and Goldsboro. In 2000, stations were located near Goldsboro and Spring Garden.

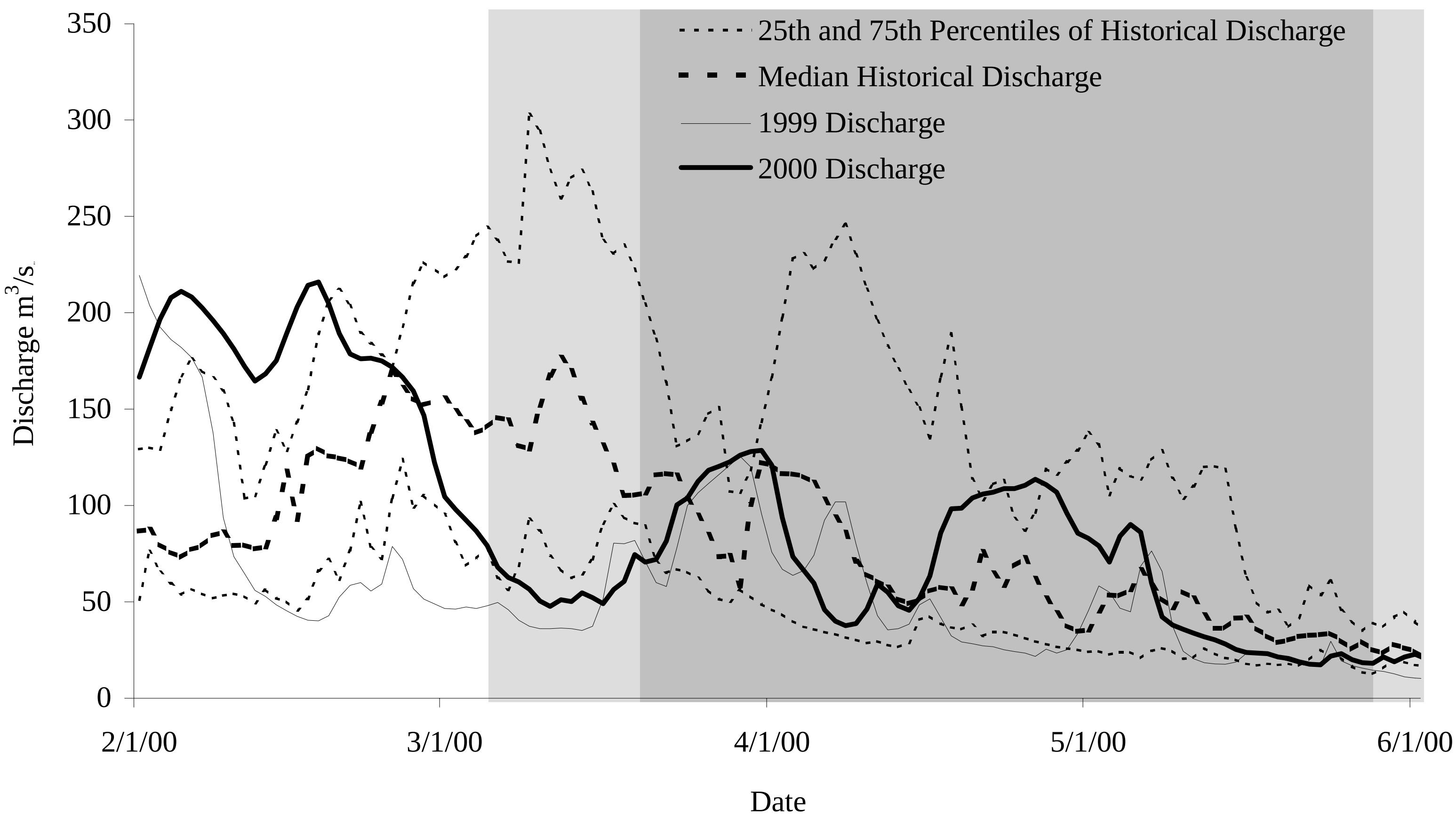

Figure 2. Daily discharges for the 1999 and 2000 field seasons and median discharges from 1984-1991 and 1994-1998, with corresponding 25th and 75th percentiles. These are the periods after construction of Falls Lake Dam for which historical discharge data were available for the USGS gaging station on the Neuse River near Goldsboro, NC. Shaded areas correspond to periods between when American shad (light shading) and striped bass (dark shading) began and ended their spawning migrations in 2000.

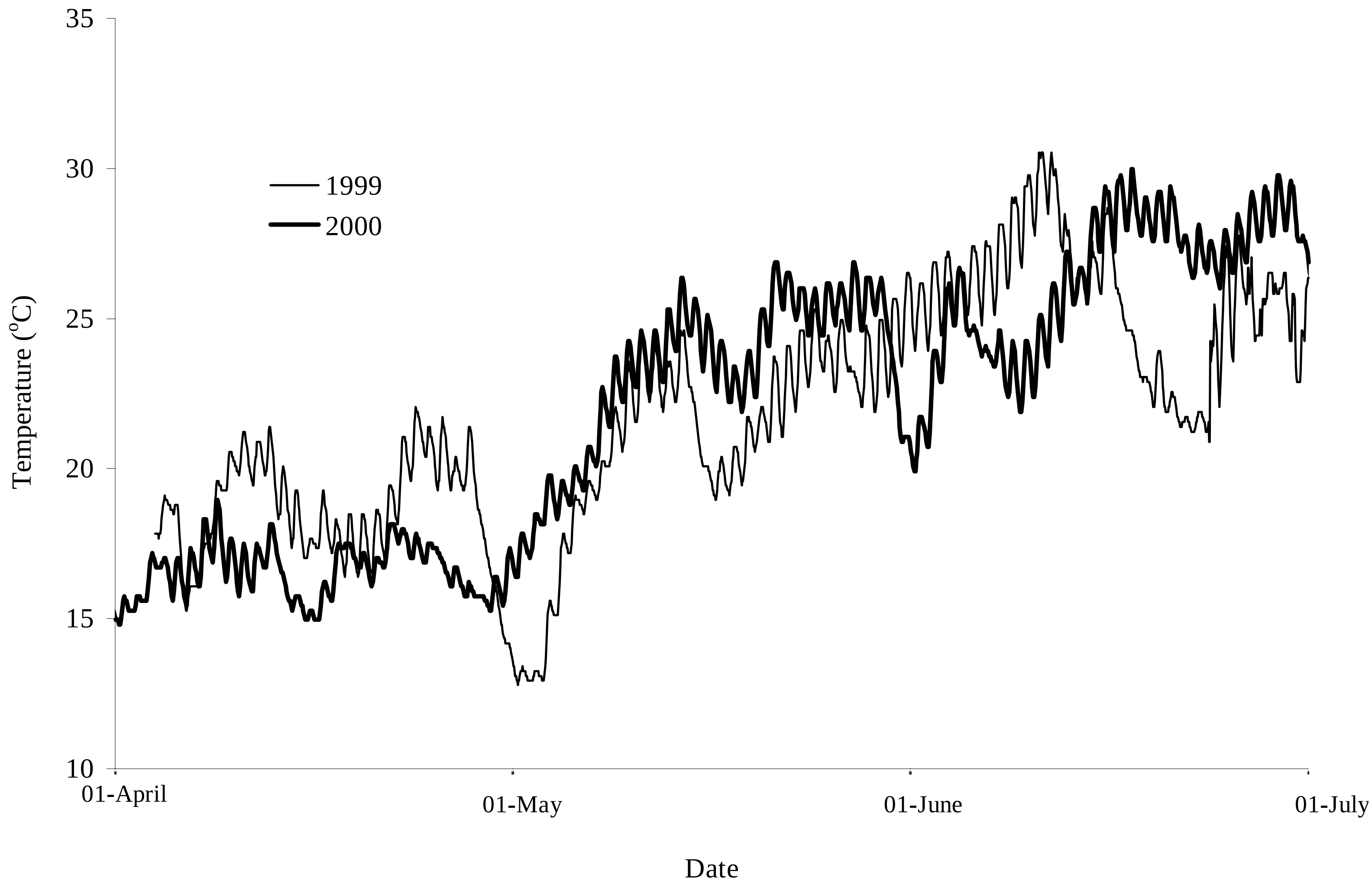

Figure 3. Neuse River water temperature time series for Goldsboro (rkm 224) throughout the 1999 and 2000 field seasons.

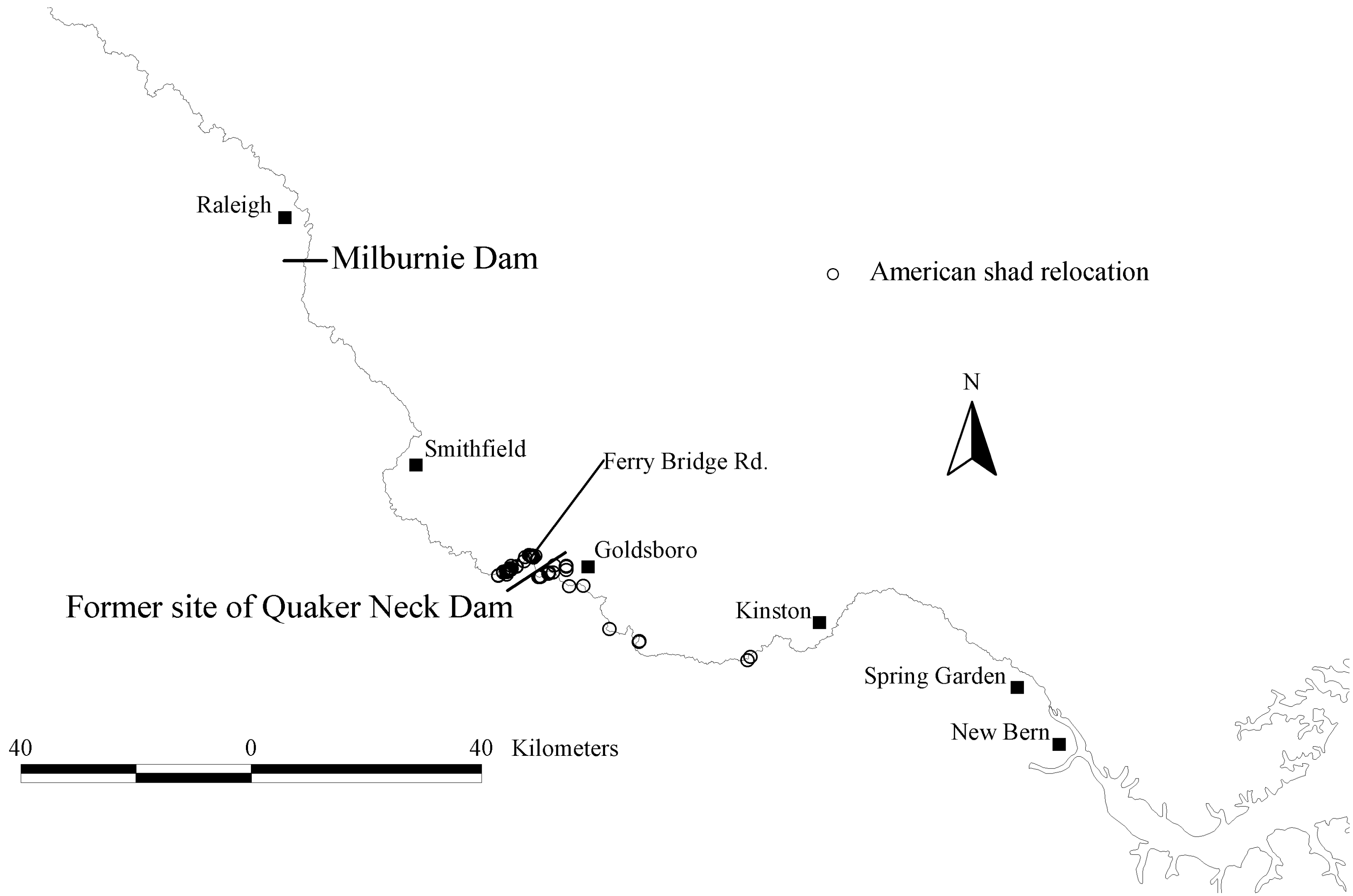

Figure 4. Relocations of radio-telemetered American shad throughout the 1999 spawning season.

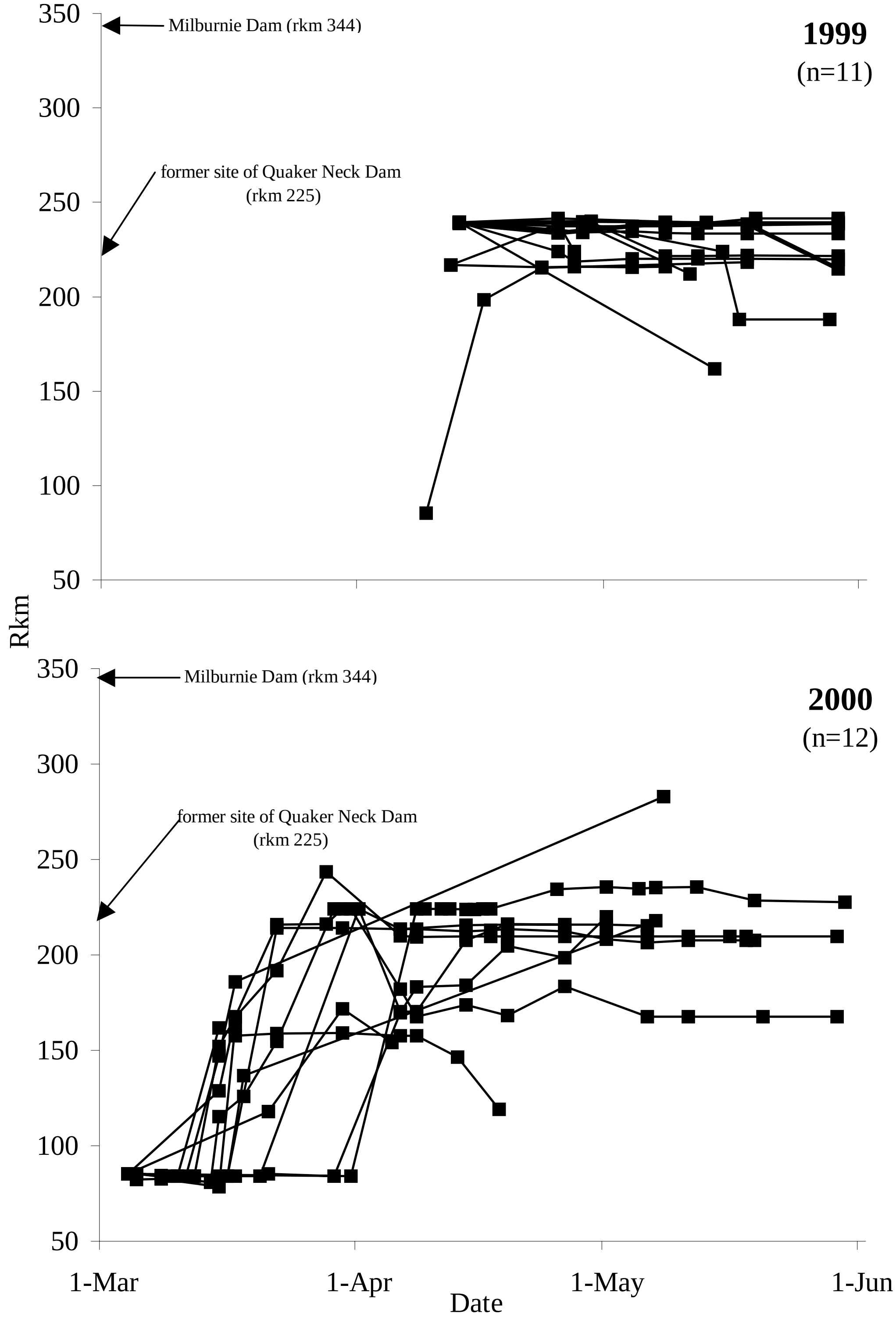

Figure 5. Location of radio-telemetered American shad by river kilometer for 1999 and 2000.

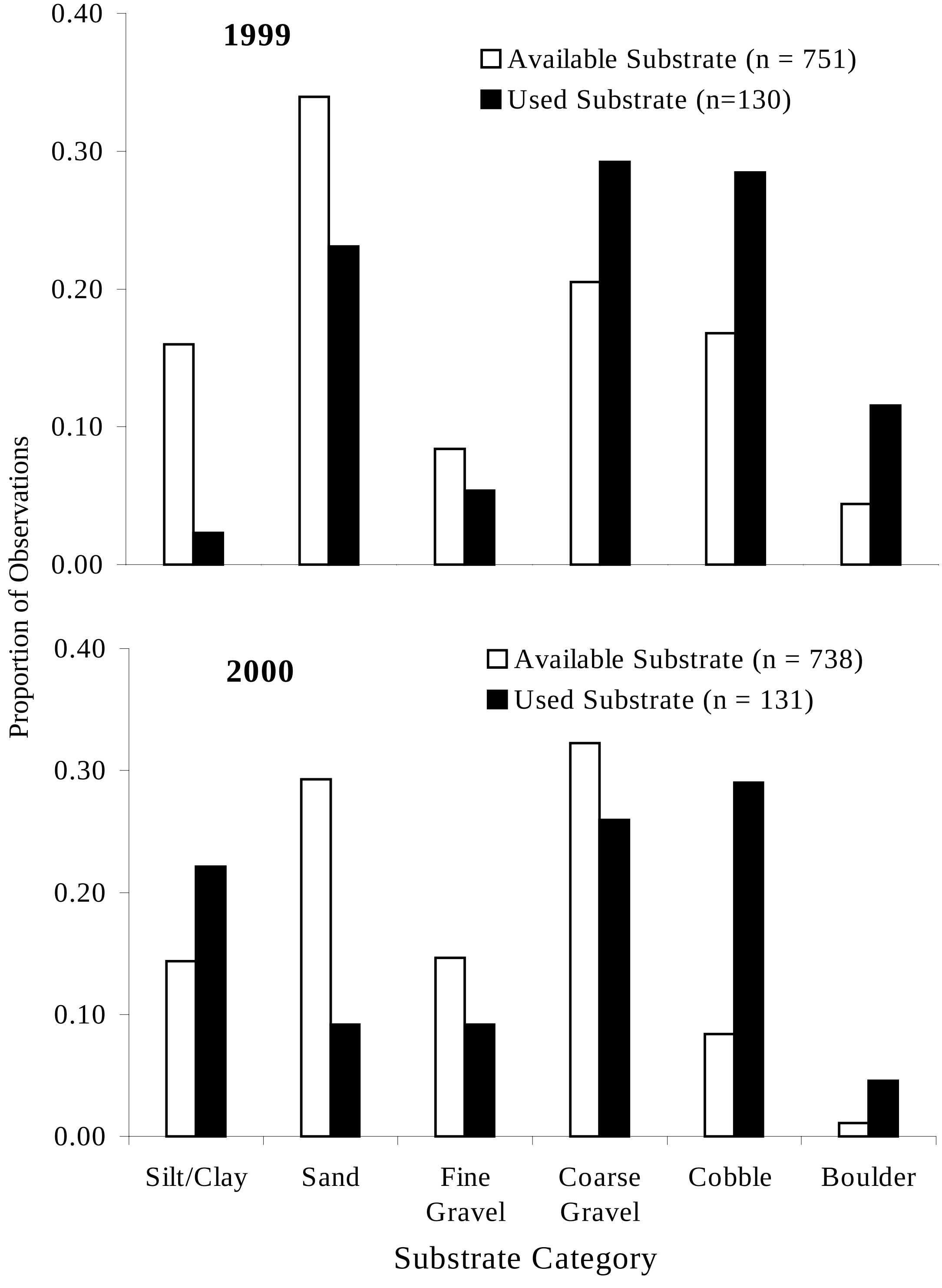

Figure 6. Frequency distribution of substrates available to and used by spawning American shad during the 1999 and 2000 field seasons. Habitat availability was measured within the primary spawning grounds occupied during 1999 and 2000.

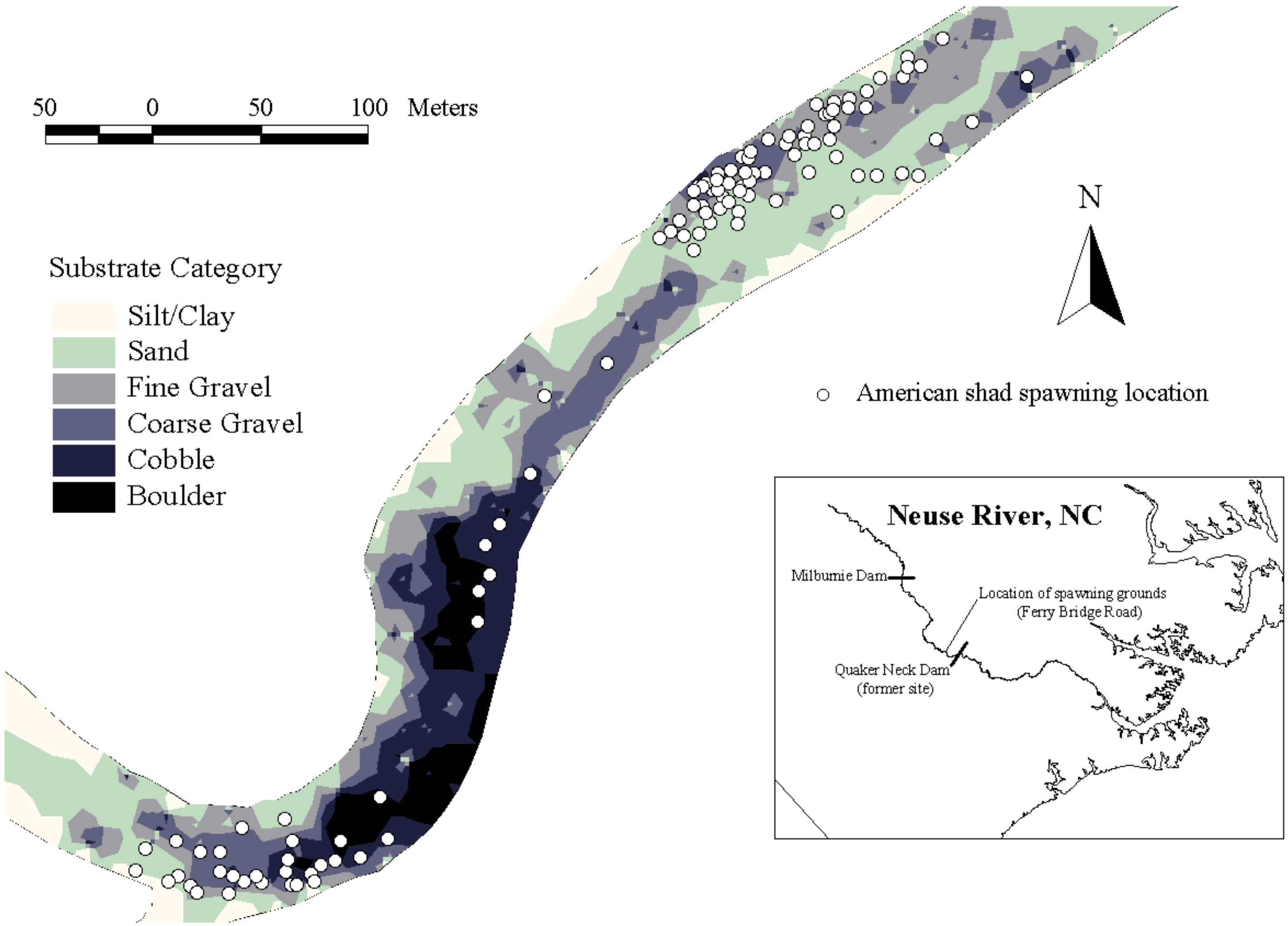

Figure 7. Contour map of substrates and American shad spawning locations at rkm 239 near Ferry Bridge Road throughout the 1999 spawning season.

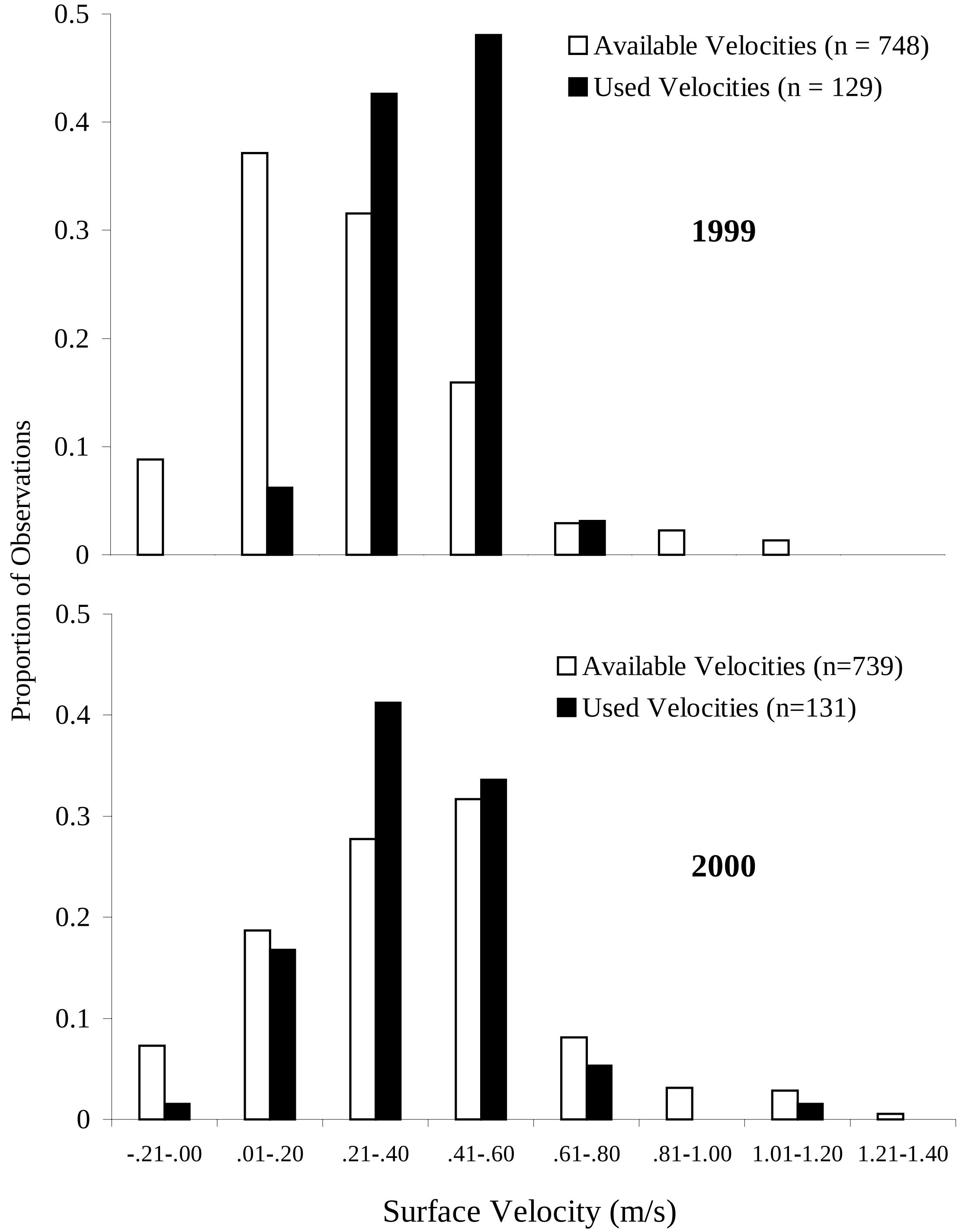

Figure 8. Frequency distribution of surface velocities available to and used by spawning American shad during the 1999 and 2000 field seasons. Habitat availability was measured within the primary spawning grounds occupied during 1999 and 2000.

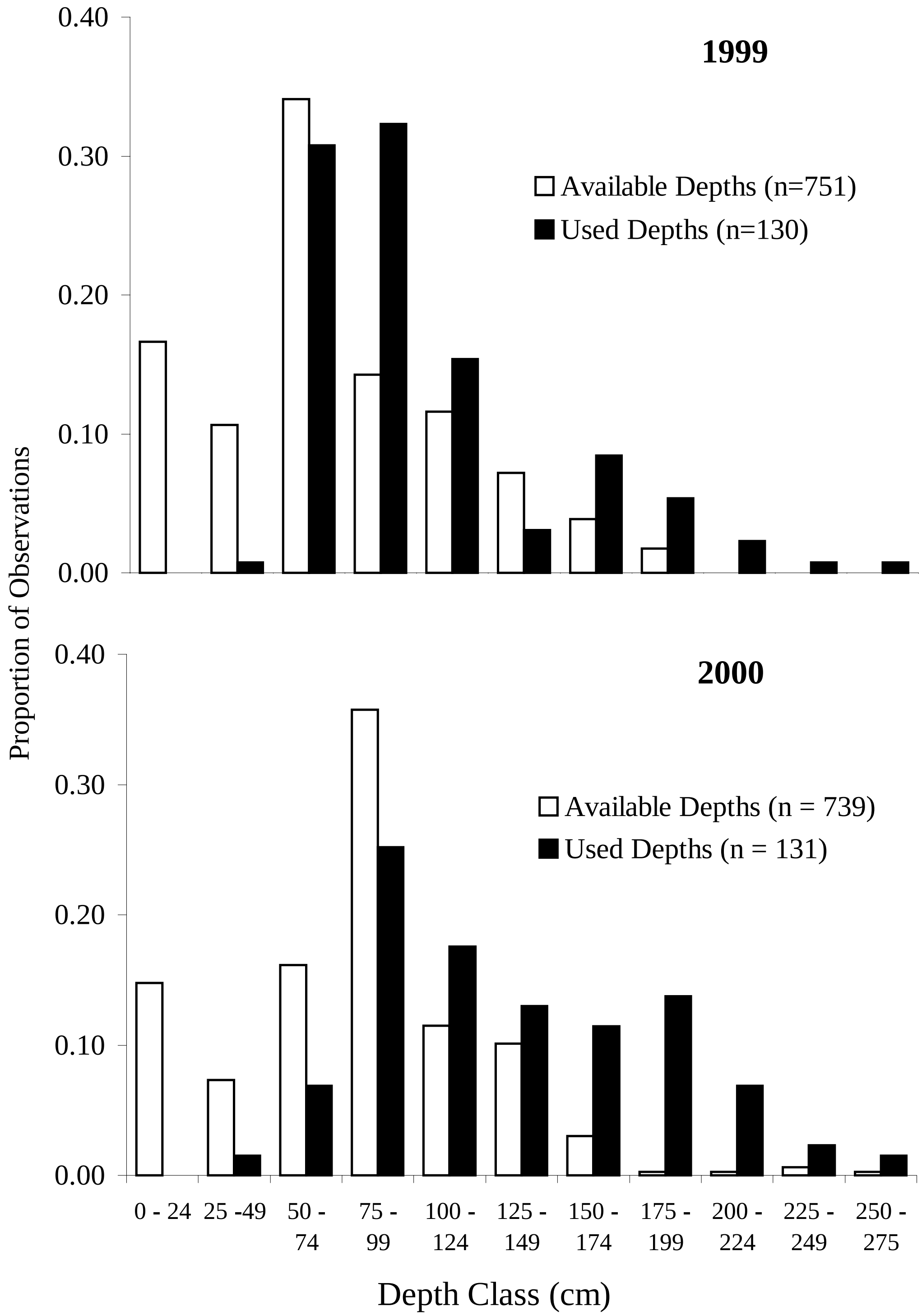

Figure 9. Frequency distribution of depths available to and used by spawning American shad during the 1999 and 2000 field seasons. Habitat availability was measured within the primary spawning grounds occupied during 1999 and 2000.

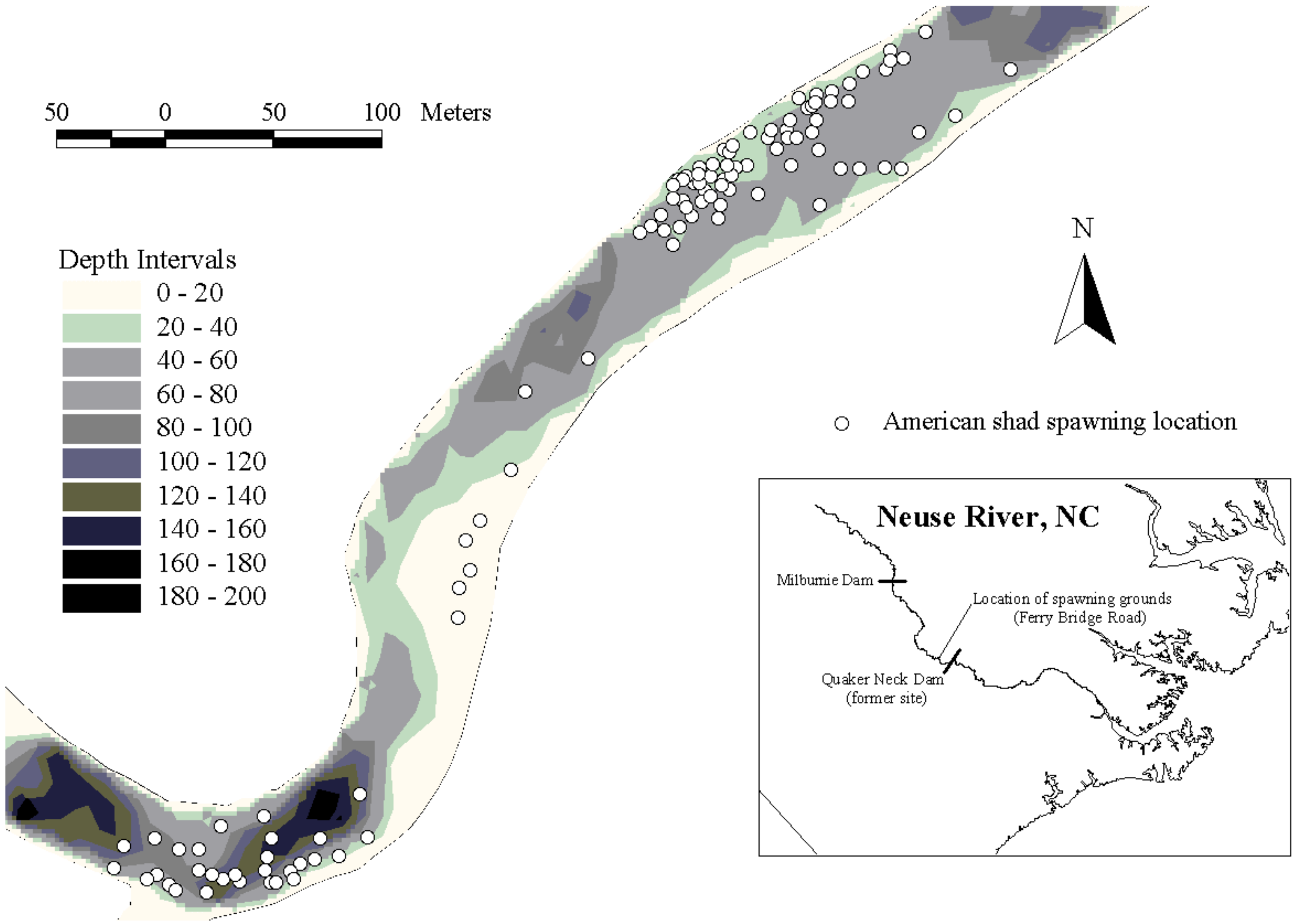

Figure 10. Contour map of depth and primary American shad spawning locations at rkm 239 near Ferry Bridge Road throughout the 1999 spawning season.

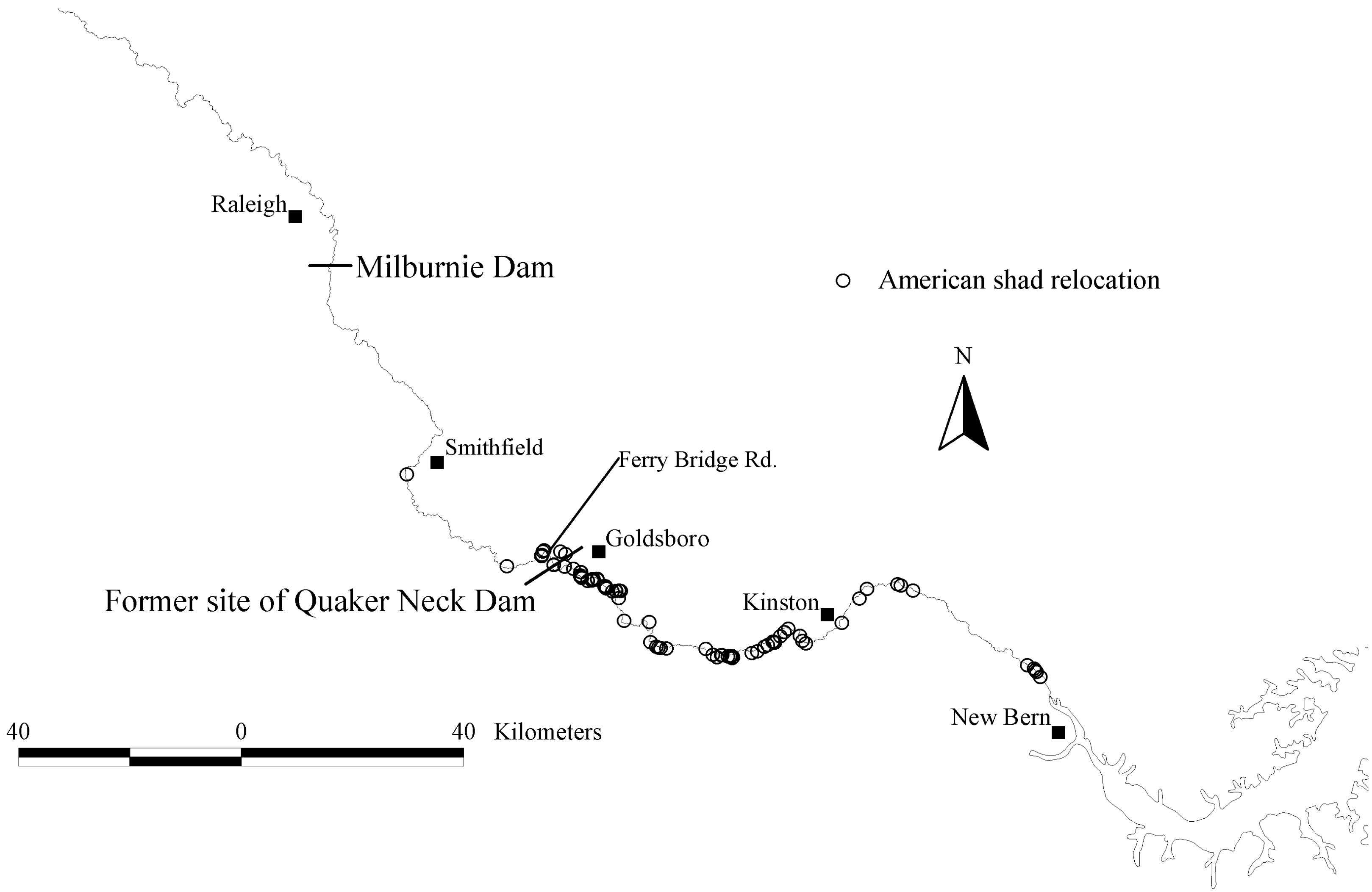

Figure 11. Relocations of radio telemetered American shad throughout the 2000 spawning season.

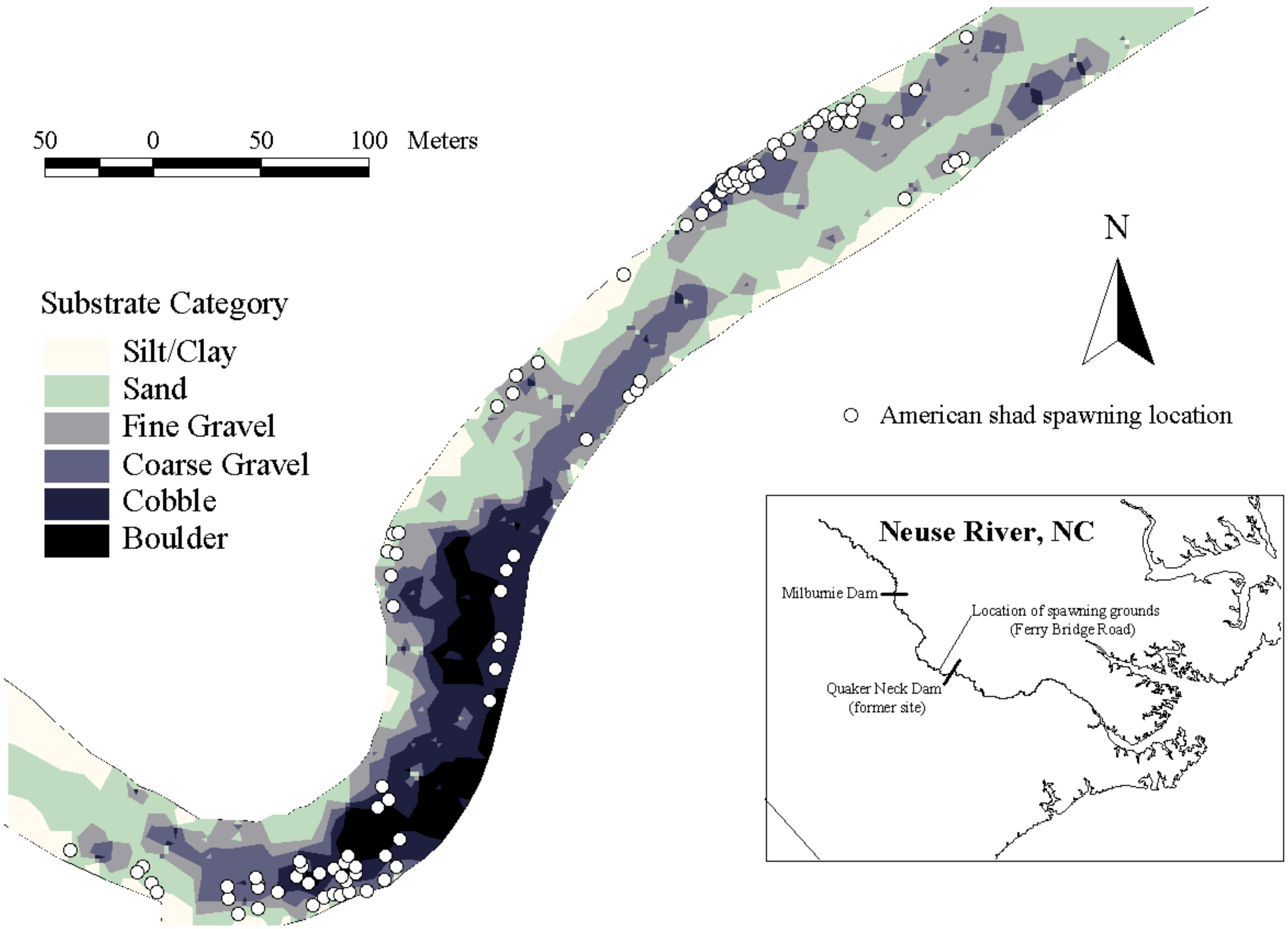

Figure 12. Contour map of substrates and American shad spawning locations at rkm 239 near Ferry Bridge Road throughout the 2000 spawning season.

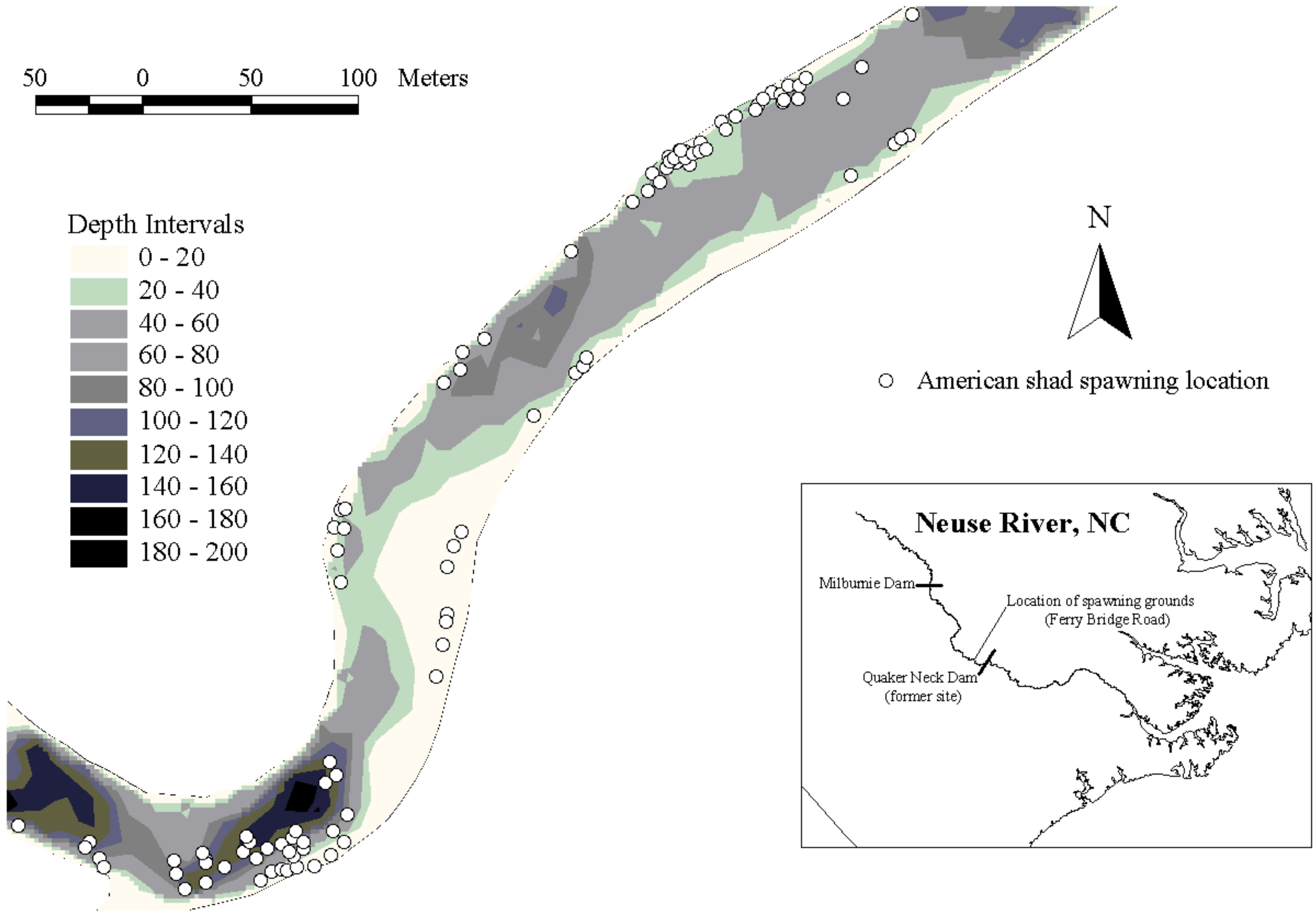

Figure 13. Contour map of depth and primary American shad spawning locations at rkm 239 near Ferry Bridge Road throughout the 2000 spawning season.

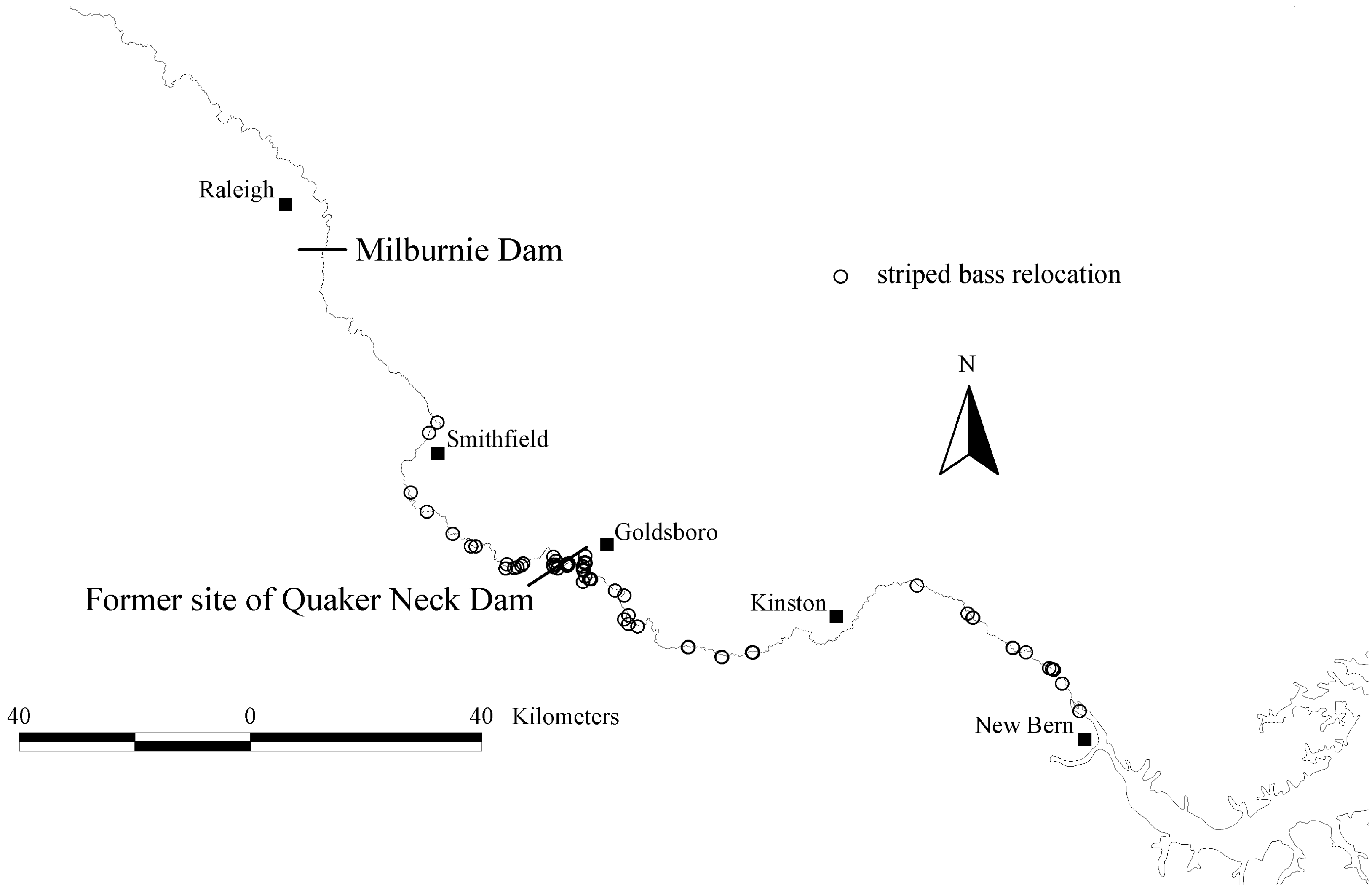

Figure 14. Relocations of radio-telemetered striped bass throughout the 1999 spawing season.

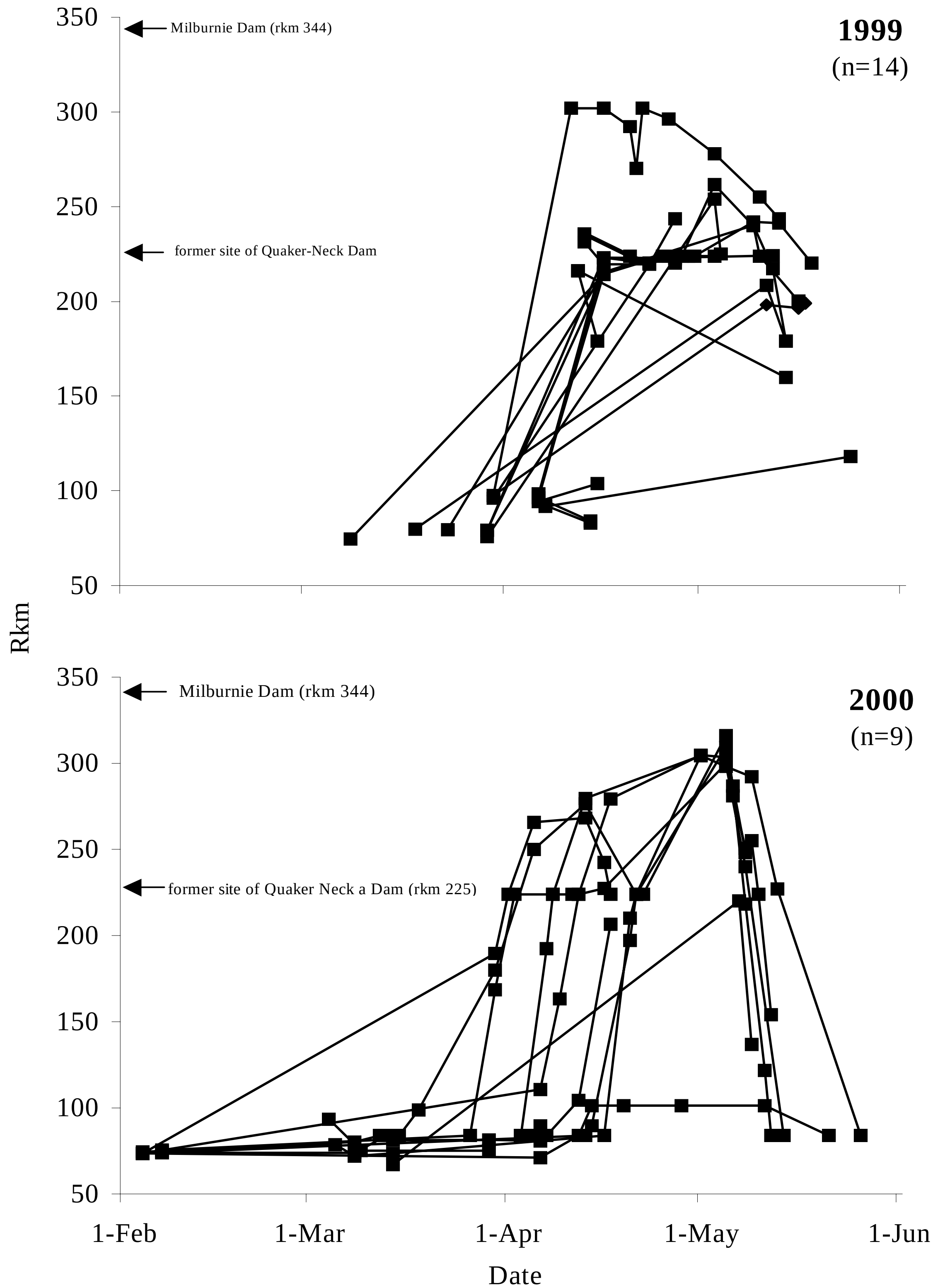

Figure 15. Location of radio-telemetered striped bass by river kilometer for 1999 and 2000.

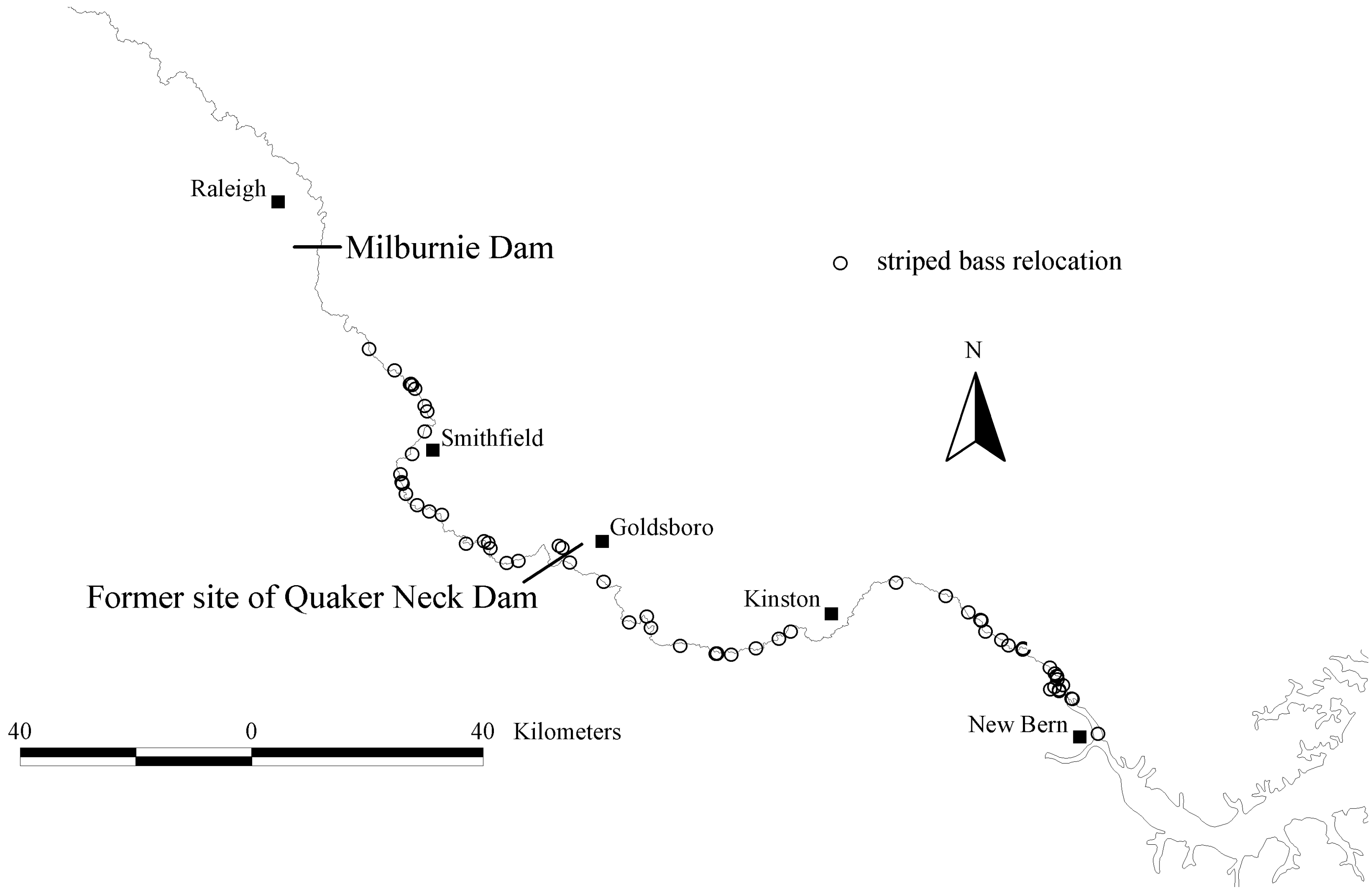

Figure 16. Relocations of radio-telemetered striped bass throughout the 2000 spawing season.