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Assessment of spawning and nursery habitat suitability for American shad (Alosa sapidissima) in the Mattaponi and Pamunkey rivers

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Assessment of Spawning and Nursery Habitat Suitability for American Shad (*Alosa sapidissima*) in the Mattaponi and Pamunkey Rivers

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A Dissertation
Presented to
The Faculty of the School of Marine Science
The College of William and Mary

In Partial Fulfillment
Of the Requirements for the Degree of
Doctor of Philosophy

By

Donna Marie Bilkovic

2000

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APPROVAL SHEET

This dissertation is submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

Donna Marie Bilkovic

Approved, December 2000

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Abstract

Fisheries Management Plans (FMPs) require the identification and protection of essential fish habitat (EFH) as mandated by the reauthorization of the Magnuson-Stevens Act in 1996. Delineation of EFH is particularly difficult for migratory fish which utilize large expanses of habitat throughout their life history. This study's main objective was the development and evaluation of habitat assessment tools for the early life stages of American shad (*Alosa sapidissima*), an anadromous fish managed with a FMP, in two coastal plain rivers of Virginia. To accomplish this, shad spawning and larval nursery habitats were first delineated in the Mattaponi and Pamunkey rivers using presence of eggs and larvae (1997-1999) as evidence of habitat use. Potential interactions of American shad and striped bass, another important fisheries species in these systems, that may affect spawning or survival of progeny were also examined. American shad eggs and larvae were more abundant on the Mattaponi River than the Pamunkey River, while the opposite pattern was apparent for striped bass eggs and larvae. There was overlap between the extreme ranges of spawning of shad and striped bass, but the primary spawning habitat of each species was spatially disjunct in both rivers (Ch. 1). Next, habitat suitability index (HSI) models were developed based on extensive literature reviews for hydrographic, physical habitat, shoreline and land use features, which are potential influences on shad production in the Mattaponi and Pamunkey rivers. (Ch. 2).

A macroscale habitat assessment protocol was developed which was used to separately rate habitat in the rivers based on hydrographic, physical habitat, shoreline and land use parameters. These parameters were also evaluated for associations with American shad eggs and larvae during 1997-1999 collections for corroboration of habitat ratings. Values for parameters used in the ratings were obtained from a variety of sources in attempts to combine best-available data. Data sources consisted of a combination of field assessments (1997-1999), long-term data sets (water quality) and remote sensing (land use). Multivariate statistical analyses indicate the importance of hydrographic parameters (current velocity, dissolved oxygen and depth); physical habitat features (sediment type and deadfall); and forested shoreline and land use features to presence of eggs. Larvae were more dispersed than eggs and distinct habitat associations could not be discerned. Morphological features indicate the presence of three distinct regions along the Mattaponi and Pamunkey river gradients. Presence of eggs is typically associated with upstream and mid-river regions, while larvae were dispersed amongst the three regions. The combination of remote sensing and on-site data collection and analyses used in this study may be an effective way to rapidly assess fish habitat when data are limited (Ch. 3).

Because shad spawning and nursery habitat is thought to fluctuate with abiotic influences, hydrographic factors hypothesized to impact spawning location, transport of larvae, development rates and predator and prey abundance were examined. Utilizing the juvenile *Alosa* index (JAI) from 1991-1999 as an estimate of juvenile shad recruitment in the Mattaponi and Pamunkey rivers, correlation with hydrographic parameters during the months March-June, including discharge, precipitation and water temperature was examined. Hydrographic conditions during May and June appear to most accurately predict patterns in juvenile recruitment in the Mattaponi River, however trends in the Pamunkey River were not as consistent. Because of the inconsistency in hydrographic controls between rivers, other possible influences were explored, including biotic, morphological, and water quality. Ultimately, discharge affects transport of weak-swimming early larva to variably favorable nursery habitats. A conceptual hydrodynamic model was developed which explores potential impacts of variable habitat exposures on larvae driven by spawning location, habitat suitability, discharge and hatching rates (Ch. 4).

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Chapter 1

Spawning of American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*) in the Mattaponi and Pamunkey Rivers, Virginia

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Abstract

Declines of American shad (*Alosa sapidissima*) populations in the Chesapeake Bay have led to fishing moratoria in Virginia and Maryland. Overfishing, blockage of spawning runs, degradation of water quality, and habitat destruction are postulated causes of population decreases. While moratoria and efforts to restore the fishery continue, it is imperative to garner information regarding quality and quantity of spawning habitat. Management efforts then may be focused on particular reaches of rivers, thus targeting areas for impediment removal, water quality improvement, and habitat protection. American shad eggs and larvae were collected in 1997-1999 as evidence of spawning habitat use. The areas of study were the Mattaponi and Pamunkey rivers, two unimpeded tributaries of Chesapeake Bay, where shad populations are low compared to historic levels, but currently at the highest level of any Virginia stock. Information from initial ichthyoplankton sampling during spring 1997 was used to modify sampling locations and techniques for the second and third year of sampling. Striped bass (*Morone saxatilis*) is thought to use similar river reaches as American shad during spawning, and interactions of these species may affect spawning or survival of progeny. Distribution and relative abundance of eggs and larvae of American shad and striped bass were compared between rivers. Temporal overlap in spawning by the two species occurred throughout the sampled period in both rivers. American shad eggs and larvae were more abundant on the Mattaponi River than the Pamunkey River by a factor of 5.5 and 4.6, respectively. Striped bass eggs and larvae were more abundant on the Pamunkey River than the Mattaponi River by a factor of 29 and 9.9, respectively. There was overlap between the extreme ranges of spawning for shad and striped bass, but the primary spawning habitat of each species was spatially disjunct in both rivers.

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Introduction

A current fisheries management target in the Atlantic coastal region is the American shad (*Alosa sapidissima*). Highly prized for its roe, spawning runs of American shad were heavily fished and the species was an important commercial resource at the turn of the century. However, since the late 1800s, there have been steady declines in landings (ASMFC 1999). In response to these population declines, Maryland declared a fishing moratorium in 1980, and Virginia followed in 1994 for the Chesapeake Bay and its tributaries. Shad restoration projects are underway to restock depleted spawning runs, especially in regions where stream impediments have been or are being removed. Coastal intercept fisheries have remained in place amongst criticism and speculation about their impact on populations, particularly those stocks that are depleted. The Atlantic States Marine Fisheries Commission Shad Board (ASMFC 1999) adopted a fishery management plan for American shad and river herring that included a five-year phase out of the ocean fishery. Each state is required to develop an approved fishing or recovery plan for each stock under restoration. In Virginia, this requirement applies to the James and York rivers.

Although the roe fishery for American shad has historically been important, there is little information about the specific spawning locations of these broadcast spawners. American shad are anadromous fish native to the Atlantic coast of North America, with a range extending from southeastern Labrador to the St. Johns River, Florida (Murdy et al. 1997). In Chesapeake Bay tributaries, American shad deposit semi-demersal eggs in the freshwater portions of the estuaries in the spring, usually beginning in March and ending by early June with peaks in April (Klauda et al. 1991). American shad have historically

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ascended farther upriver than at present, within tributaries with impediments. Prior to dam building in the James River, large numbers of American shad traveled over 335 miles from Chesapeake Bay into the Jackson and Cowpasture tributaries (Mansueti and Kolb 1953). In the York River, the upper limits of shad spawning are unknown.

The York River, a coastal plain tributary located in the Chesapeake Bay watershed, is formed by the confluence of the Pamunkey and Mattaponi Rivers at West Point (Figure 1.1). The Pamunkey River has a larger watershed (3,768 km^2) and average spring discharge rate (47.5 m^3/s) than the Mattaponi River (2,274 km^2; 27.2 m^3/s, respectively) (Watershed sizes based on USGS Digital Line Graph Data (DLG) at 1:100,000). On these unimpeded rivers, annual releases of hatchery-reared American shad reach two to four million through efforts of the Virginia Game and Inland Fisheries (VGIF) and an estimated 2.5 to 3 million fry released from the Pamunkey tribal government, with unknown contributions from the Mattaponi tribal government (T. Gunther, personal comm.). Current monitoring of adult catches indicates that the York River currently supports the strongest runs of shad in Virginia (Olney and Hoenig 2000). American shad in the York River are used as the source stock for hatchery efforts in the James and Potomac rivers. Thus, the restoration efforts in Virginia are dependent on the productivity of the York River.

Throughout the freshwater tidal portions of the Mattaponi and Pamunkey rivers, numerous other species spawn including striped bass (*Morone saxatilis*), another commercially and recreationally important anadromous species along the East Coast of

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the United States. The Chesapeake Bay stock has rebounded after severe declines in the 1970s and early 1980s probably due to successful management and several years of successful reproduction (Olney et al. 1991; Field 1997). Striped bass spawn upriver from the limit of brackish water in the tributaries of the Chesapeake Bay from early April through the end of May (Setzler-Hamilton et al. 1981). McGovern and Olney (1996) noted that the lower limit of striped bass spawning followed the 1 ppt. salinity contour, and Secor and Houde (1995) postulated that the freshwater-saltwater interface may act as a down-river barrier to striped bass egg and larval advection.

Water temperature is believed to be an important abiotic factor influencing both American shad and striped bass survival. Thus, changes in spawning distributions of striped bass might be reflected in similar changes in American shad. Based on suitable temperature ranges (12-24°C for striped bass (Setzler –Hamilton et al. 1980; Rutherford and Houde 1995) and 12-25°C for American shad (Walburg and Nichols 1967; Leach and Houde 1999)) and salinity requirements for the early life stages of these species, the potential for spawning overlap spatially and temporally is high. Species interactions, including predation and competition by both adults and young, may play a role in the spawning and recruitment success of these species. Similar interactions have been postulated between American shad and other alosines in the Hudson River (Schmidt et al. 1988).

The first objective was a descriptive spatial-temporal study to identify American shad spawning reaches in the Mattaponi and Pamunkey rivers. The second objective was to

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determine if striped bass spawning was occurring within the identified spawning habitat of American shad. In year one, an exploratory survey was completed to map the distribution of American shad spawning grounds and the co-occurrence of striped bass within these reaches. In years two and three, sampling was modified to locate the upper limit of American shad and striped bass spawning within the two rivers.

Methods

Sampling Protocol in 1997

Exploratory sampling in the Mattaponi and Pamunkey rivers for eggs and larvae of American shad and striped bass extended from March through April 1997. Sites were chosen based on anecdotal information, and a prior survey of American shad eggs in the rivers (Massmann 1952). Sampling protocol included weekly ichthyoplankton collections during daylight hours using stepped oblique tows of a bongo frame fitted with two 333 μm mesh nets (60 cm diameter). Catches from both nets were combined. The same ten stations were sampled on each river weekly within the tidal freshwater reaches. Stations are depicted as river kilometers from the mouth of the York River, for example, M68 is a station on the Mattaponi River that is approximately 68 river kilometers from the mouth of the York River. The stations were located at approximately 3.2-Rkm (two river mile) intervals within the range of 72 to 106 Rkm (P72 to P106) on the Pamunkey River and 68 to 102 Rkm (M68 to M102) on the Mattaponi River (Figure 1.1).

Sampling Protocol in 1998 and 1999

In 1998 and 1999, station locations were extended upriver to include more shallow stations due to the low abundance of American shad eggs at downriver stations in 1997.

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These new shallow stations required a different sampling gear, so ichthyoplankton sampling in 1998-1999 was modified to consist of two parts: pushnet surveys and stationary net collections. The first protocol was utilized in the upper reaches of the Mattaponi and Pamunkey rivers from 31 March through 20 May 1998 and from 11 April through 7 May 1999. The sampling on each river consisted of weekly pushnet deployments for a five to seven minute duration at approximately one meter below the surface at each station. A pushnet frame was fitted to the bow of a 14-foot boat and accommodated two plankton nets of equal mesh and diameter (333 μm, 60 cm). Catches from both nets were combined. In 1998, eight stations per river were systematically sampled in the river segments bracketing River kilometers 94 to 120 (M94 to M120) on the Mattaponi River and kilometers 109 to 131 (P109 to P131) on the Pamunkey River. In 1999, two upriver stations were added on the Mattaponi River (M124 and M128); on the Pamunkey River, we added six upriver stations (P135-P154) and one downriver station (P104). As in 1997, these stations were spaced at 3.2-Rkm (two river miles) intervals (Figure 1.1). Bongo and push nets were fitted with a flow meter for volumetric measurements. Tow duration was adjusted from three to seven minutes to meet a lower limit of 50 m^3 of water filtered through both nets combined.

Stationary nets, located in shallow, nearshore habitats, were fished by community volunteers at designated locations. Stations were located along the Mattaponi River from kilometer 78 through 115 (M78 through M115) (Figure 1.1), and the nets (20 cm diameter, 202 μm mesh) were fished for a 24-hour period once a week. Volunteers were trained in retrieval and preservation of samples. In 1998, volunteer sampling began 4

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April and ended 31 May; in 1999, 12 April through 17 May. In 1999, in conjunction with volunteer sampling periods, stationary nets were also placed on the Mattaponi and Pamunkey rivers in upriver locations not accessible by boat (P139, P152, P163, P176, M122 and M139).

Laboratory Procedures

Ichthyoplankton samples were preserved in 10% phosphate-buffered formalin. Ichthyoplankton were sorted and larval fish and eggs were enumerated and removed from the original, whole sample. Striped bass and American shad eggs were distinguished by the presence or absence of an oil globule. White sucker (*Catostomus commersoni*) eggs can be confused with those of American shad, but do not occur below the fall line in the York River where sampling was conducted (Ross and Bennett 1993; Jenkins and Burkhead 1994). *A. sapidissima* larvae were distinguished from other clupeids by the number of preanal myomeres, number of postanal myomeres, relative preanal length and pigmentation patterns (Lippson and Moran 1974; Jones et al. 1978). Densities were reported for American shad and striped bass as number per 100 m^3. Estimates of ichthyoplankton density from stationary nets were unavailable since the volume of water filtered during the 24-hour sampling period was unknown. To estimate relative abundance in both rivers, average density of each life stage (egg, yolk-sac larva, and post-yolksac) was multiplied by total volume of spawning or nursery area sampled. Total volumes were determined separately for each species by including locations within the sampling region where eggs (spawning reaches) or larvae (nursery reaches) were collected. River volumes were calculated using bathymetric surveys and corresponding areal estimates from a digitized record of the mean high water shoreline position as

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shown on the U.S. Geological Survey 7.5 minute topographic map series completed by Comprehensive Coastal Inventory, Virginia Institute of Marine Science (see Chapter 3).

Ancillary data

For purposes of comparison, we used data on the abundance of American shad and striped bass juveniles in the Pamunkey and Mattaponi rivers. The data result from annual surveys of juvenile abundance conducted by the Virginia Institute of Marine Science (Olney and Hoenig 2000; Austin et al. 2000).

Results

Trends in density (numbers/100m^3) for each river, species and life stage by date and station are depicted for 1997-1999 in Figures 1.2-1.6. Average density (total eggs or larvae per total volume filtered) of each species per river is depicted in Figure 1.7. On the Mattaponi River (1997-1999), American shad eggs were collected over a 44-km reach (M81-M124), with the highest densities occurring between M98 and M124 (Locust Grove through upstream of Herring Creek) (Figures 1.2 and 1.4). Striped bass spawning occurred over a 27-km reach with the highest densities occurring between M68– M87 (Heartquake Creek through Mantapike), downstream of the primary spawning reaches of American shad (Figures 1.5, 1.7 and 1.8a).

On the Pamunkey River, American shad eggs were collected over a 53-km reach (P98-P150; Lester Manor through Dabney's Mill), with the highest densities occurring from P104-131 (Figure 1.2). Striped bass spawning occurred over a 60-km reach (P72-P131), with the highest densities occurring from P72-P87 (Figure 1.5). There was some spatial

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overlap in spawning of these species, but the primary spawning reaches were separate (Figure 1.8b). Temporal overlap in spawning of American shad and striped bass occurred throughout the sampling period in both rivers (Figures 1.2, 1.4 and 1.5).

On the Mattaponi River, American shad larvae (total length, 6.1–19.2 mm) were collected from M68–M124, with the highest densities observed between M94-M102 (Rickahock through Whitehall), a reach that is downstream of the spawning habitat (Figures 1.3 and 1.7). On the Pamunkey River, American shad larvae (total length, 6.6-12.2 mm) were collected between (P72-P128; Hill Marsh through Pampatike). Densities were highest at P102, 104 and 124 (Figures 1.3 and 1.7). Larval striped bass were collected from M68-M94 and P72-P109, with peaks (> 1 m^{-3}) from M68-M80 and P72-P91 (Figure 1.6). In both rivers, overlap was observed in American shad nursery grounds and striped bass spawning reaches. However, the highest densities of larval striped bass were downstream of primary shad spawning and nursery areas (Figure 1.7).

Average density of individual life stages of American shad was higher in the Mattaponi River than in the Pamunkey River: the opposite pattern was apparent for striped bass (Table 1.1). Estimates of the relative numbers of American shad and striped bass (average density x river volume) suggested that abundance of American shad eggs and larvae was higher on the Mattaponi River than the Pamunkey River by a factor of 5.5 and 4.6, respectively. Relative abundance of striped bass eggs and larvae was higher on the Pamunkey River than the Mattaponi River by a factor of 29 and 9.9, respectively (Table 1.2).

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Discussion

Over the three years of surveys, eggs and larvae of American shad were rare compared to those of striped bass (Table 1.1). Despite successive efforts to relocate sampling stations farther upstream and above known striped bass spawning habitat (Grant and Olney 1991; Olney et al. 1991), their eggs and larvae were more abundant (~ 114 times and ~ 38 times, respectively) than those of American shad (Table 1.2). These differences could be attributable to the relative sizes of the spawning stocks since the number of mature American shad presently in the York River system is believed to be low relative to historic run size (Nichols and Massmann 1963; Olney and Hoenig in review). In contrast, striped bass stocks are large and support a large recreational and commercial fishery in the York River. In support, although collections in this study did not cover the entire downstream reaches of striped bass spawning habitat, eggs were observed in higher peak densities in the Pamunkey River by an approximate factor of 10.7 than peak densities observed by Grant and Olney (1991) when striped bass spawning stock size was lower than current levels. In the Mattaponi River, this study did not sample within peak spawning reaches for striped bass, but in comparable locations sampled in both this study and the study by Grant and Olney (1991), peak densities were higher in this study by a factor of approximately 4.7.

There are alternative explanations for the scarcity of American shad eggs and larvae, however. The low numbers could be due to sampling bias including the inadequacy of the station grid to fully bracket the spawning habitat, the low catchability of American shad eggs and larvae by the gear, or both factors. It is difficult to evaluate the former bias since shallow depths and natural obstructions prevented sampling farther upstream in

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either river by boat, and deployment of stationary nets across a wider geographic area required access to sites that were under private ownership. On the point of catchability, Maurice et al. (1987) and Ross et al. (1993) collected large numbers of American shad eggs and larvae in the Delaware River using bongo nets and deployment methods that were similar to those used in this study. Pushnets have not been previously used in ichthyoplankton surveys for American shad but have been shown to be effective samplers in shallow systems (Olney and Boehlert 1988). I did not evaluate catchability of shad eggs and larvae in the gear, but noted only small differences in average density of eggs and larvae in bongo and push-net collections in the Mattaponi and Pamunkey rivers (Table 1.3). In the Delaware River, densities of American shad eggs were low (< 1 egg/100 m^3) but the overall ratios of eggs to larvae in the collections of Maurice et al. (1987) and Ross et al. (1993) were very high compared to my findings (Table 1.3). However, summaries of other ichthyoplankton surveys in different years and locations in the Delaware River suggest that American shad egg:larval ratios vary widely (Maurice et al. 1987; their Table 1). Densities of larval American shad were higher at night in the Delaware River (Maurice et al. 1987), an observation that probably accounts for the low densities of larvae in my daylight collections. Several researchers noted that American shad spawn in early evening or night hours (Leim 1924; Ross et al. 1993; T. Gunther, personal comm.); thus, vulnerability of eggs to capture by plankton nets may be higher at night if sinking rates are rapid. Scarcity of American shad eggs in daylight plankton tows has also been noted by Marcy (1976).

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Despite the proximity and resemblance of the Pamunkey and Mattaponi rivers, patterns of spawning and recruitment of American shad and striped bass are opposite on each tributary. Annual differences in abundance of eggs and larvae of these species observed in this study are concordant with historic trends in juvenile production. In the current study, eggs and larvae of American shad were more abundant on the Mattaponi River and striped bass eggs and larvae were more abundant on the Pamunkey River (Table 1.1 and 1.2). Similarly, mean recruitment (the mean index of juvenile abundance or JAI) of American shad was higher on the Mattaponi River (1991-1999: Mattaponi JAI-1,522.6; Pamunkey JAI-247.0), and mean recruitment of striped bass was higher on the Pamunkey River (1980-1999: Mattaponi JAI-2.4; Pamunkey JAI-3.4). The approximate volume of the Pamunkey River, from the fall line to the river mouth (1.9×10^8 m^3) is 1.2 times that of the Mattaponi River (1.6×10^8 m^3). Thus, equal populations of eggs or larvae that are homogeneously distributed on each tributary would be expected to be at the most 1.2 times as concentrated on the Mattaponi River. It is unlikely that tributary volume alone is responsible for the contrasting patterns, since observed differences in egg density were much greater than double (~17 times in the case of striped bass) and in the unexpected direction (Pamunkey River egg densities > Mattaponi River egg densities). Instead, differences in discharge, river sinuosity, habitat, stock size or combinations of these factors may be responsible.

In the York River system, American shad spawn in shallow upstream locations, and larvae rapidly disperse downstream. In each year of sampling, larvae were collected farther downstream than were eggs (Figure 1.9). In laboratory experiments that ignored

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hydrodynamic and tidal influence, egg sinking rates were 0.5-0.7 m/min (1.6-2.4 ft/min) depending on age of the egg, with the higher rates attributed to newly spawned eggs (Massmann 1952; Chittenden 1969). Most eggs collected in this study were typically in early developmental stages, supporting the idea that later stages are unavailable to plankton nets. Leim (1924) and Massmann (1952) noted similar results in their egg collections, and Leim attributed this observation to the demersal character of the eggs. Based on these fast sinking rates and lack of later stages in collections, it may be presumed that eggs of American shad reach the bottom soon after spawning and may remain near spawning areas depending on the bottom structure. In the upriver reaches of the Mattaponi and Pamunkey rivers, extensive deadfall and other debris structures may serve to maintain eggs near spawning sites. Downstream where such structure may be absent, eggs could be transported to unfavorable locations.

Upon hatching, American shad larvae swim weakly near the surface, passively sink and then repeat the repertoire (Leim 1924; Chittenden 1969), a behavior typical of clupeiform larvae (Hunter 1981). This behavior quickly displaces larvae downstream of the principal spawning areas as is evidenced by my data. Depending on the extent of downstream drift, a larva may experience varying degrees of favorable or unfavorable nursery habitat. A hydrodynamic model was used to examine the influence of tides and discharge rates on the distribution of American shad eggs and early larval stages under varying flow conditions and spawning locations (see Chapter 4).

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Temporal and some spatial overlap in spawning distributions of American shad and striped bass occurs in the York River system, but the primary spawning grounds of these species are disjunct (Figures 1.8a and b). Evidence of spawning and peak egg abundance for both species was apparent throughout the water temperature range of 13-19°C in both rivers. Trends of general abundance for both rivers indicate that American shad have a spawning distribution in regions upstream of striped bass primary spawning grounds (Figure 1.7). Trophic interactions, especially predation and competition may explain the disjunct spawning habitats of these species in the York River. Striped bass are potentially important predators on American shad in freshwater (Mansueti and Kolb 1953; Walburg and Nichols 1967). Although recent studies have failed to detect American shad in the diets of striped bass (Manooch 1973; Austin and Walter 1998), this absence may be due to current low numbers of American shad in relation to other clupeids. Conversely, juvenile American shad have the potential to prey upon striped bass larvae (McGovern and Olney 1988). Competition for food may occur between the early life stages of these two species as well. Striped bass larvae feed on cladocerans and calanoid copepods (Setzler-Hamilton et al. 1981), while juveniles feed on a variety of food items, including insects, copepods, cladocerans, chironomids, polychaetes, larval fish, mysids and amphipods (Markle and Grant 1970; Gardinier and Hoff 1982). Larval American shad consume chironomid larvae and pupae, trichopteran larvae, cyclopoid copepodites and *Bosmina* spp. (Crecco and Blake 1983; Johnson and Dropkin 1997). Juvenile shad are thought to be opportunistic with general selection for chironomid larvae and pupae, adult terrestrial insects and trichopterans with potential shifts in prey items as juvenile size and river location vary (Ross et al. 1997). In the Mattaponi and Pamunkey

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rivers, Massmann (1963) noted that insects were the most important prey item for juvenile shad. Thus, some overlap in prey items is evident and distinct spawning locations of these species may act to minimize competition in larval and early juvenile stages which use nursery locations downriver of spawning reaches.

There is also potential overlap in habitat use between the juveniles of these species since both occupy shallow nearshore waters. Some habitat overlap may be avoided by differing inshore-offshore diel migration patterns. American shad occupy nearshore areas during daylight and move offshore during night hours (Schmidt et al. 1988), while striped bass have been observed to predominately occupy nearshore habitats during both day and night hours (Boynton et al. 1981; Rudershausen and Loesch 2000).

Locations of striped bass spawning grounds on the Mattaponi and Pamunkey rivers correspond to those of previous studies. Primary spawning reaches on the Pamunkey River were previously reported from 8-48 km above West Point (Rinaldo 1971); at approximately 27 km (Pamunkey) and 14 km (Mattaponi) above the mouth of each river (Tresselt 1952); and within the first 40 km of tidal freshwater of both rivers (Grant and Olney 1991). In the present study, some striped bass eggs were collected on the Pamunkey River upstream of previously reported locations, but at a lower abundance than occurred downstream. In the Mattaponi River, striped bass eggs were absent in upstream locations, an observation in agreement with previous surveys (Tresselt 1952; Rinaldo 1971; Grant and Olney 1991; McGovern and Olney 1996).

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On both rivers. American shad were collected in higher abundance upriver of previously reported primary ranges by Massmann (1952). He observed peak egg abundance from Lester Manor (96.2 - 98.1 Rkm) to Gregory's Bar (109.2-111.0 Rkm) on the Pamunkey River and from Mattaponi (81.4-83.3 Rkm) to Rickahock (92.5 - 94.4 Rkm) on the Mattaponi River. In part, this may be due to the fact this study sampled further upriver than Massmann, however, in those reaches sampled by both studies, eggs were found in higher abundance in this more recent study. Shifting spawning habitats, (possibly due to changes in population size, climate, or river discharge), sampling deficiencies, unknown catchability differences between the studies or some combination of these factors may explain these historical differences. As populations of American shad fluctuate, spawning reaches will likely expand or shrink. If restoration efforts are successful the availability of suitable spawning areas may become limiting. Therefore, further studies of habitat suitability for spawning within this system were conducted to elucidate potential spawning reaches and optimal areas (Chapters 2 and 3).

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Table 1.1. Average density (total numbers/total volume filtered) of eggs and larvae of American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*) collected in the Mattaponi and Pamunkey rivers, Virginia (1997-1999). Values are reported as numbers per $100m^3$.

Species	River	Eggs	Yolksac	Post-yolksac	Total Larvae
American shad	Mattaponi	59.1	32.8	67.3	100.1
	Pamunkey	33.7	11.5	6.2	17.6
Striped Bass	Mattaponi	205.3	392.1	792.4	1184.5
	Pamunkey	4016.5	2625.9	909.8	3535.7

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Table 1.2. River volume of spawning and nursery reaches (10^7 m^3), relative abundance (average density x river volume, numbers x 10^8) and ratios of eggs and larvae of American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*) collected in the Mattaponi and Pamunkey rivers, Virginia (1997-1999). River volume of reaches where eggs and larvae were found was based on bathymetric surveys and areal estimates from a digitized record of the mean high water shoreline position as shown on the 7.5 minute topographic map series of the U.S. Geological Survey.

	Volume		Relative Abundance			
	Spawning Reaches	Nursery Reaches	Eggs	Yolksac	Postlarvae	Total larvae
American shad						
Mattaponi	6.1	9.4	0.36	0.27	0.63	0.94
Pamunkey	1.9	12.0	0.07	0.13	0.07	0.21
Mattaponi: Pamunkey	3.2	0.8	5.5	2.0	8.8	4.6
Striped bass						
Mattaponi	7.9	3.3	1.6	1.3	2.6	4.0
Pamunkey	12.0	11.0	47.0	29.0	10.0	39.0
Pamunkey: Mattaponi	1.5	3.3	29.0	22.3	3.8	9.9

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Table 1.3. Average densities and ratios of American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*) eggs and larvae in the Mattaponi, Pamunkey and Delaware rivers. Only previous studies that reported values for both eggs and larvae are summarized. Abbreviations in the table are as follows: Del = Delaware River, Mat = Mattaponi River and Pam = Pamunkey River, Del = Delaware River, Drift = drift net, Bongo = bongo net, Pushnet = push-net, Stationary = stationary net, ave. dens. = average density (#/m^3), cts = overall counts and #/hr = number of eggs or larvae per hour.

Year	River	Gear Type	Eggs	Yolksac Larvae	Post Larvae	Ratio Eggs:Larvae	Source
A. sapidissima							
1992	Del	Drift (ave. dens.)	22.57	0.11	1.20	17.2	Ross et al. 1993
1992	Del	Bongo (ave. dens.)	48.40	0.22	0.30	93.1	Ross et al. 1993
1981-84	Del	Bongo (cts.)	18555		7033	2.6	Maurice et al. 1987
1997	Mat& Pam	Bongo (ave. dens.)	0.20	0.34	0.43	0.3	This study
1998	Mat&Pam	Pushnet (ave. dens.)	0.55	0.16	0.29	1.2	This study
1999	Mat&Pam	Pushnet (ave. dens.)	0.32	0.11	0.57	0.5	This study
1998	Mat	Stationary (#/hr)	0.06	0.002	0	30	This study
1999	Mat	Stationary (#/hr)	0.006	0	0	N/A	This study
M. saxatilis							
1997	Mat&Pam	Bongo (ave. dens.)	45.30	32.30	19.40	0.9	This study
1998	Mat&Pam	Pushnet (ave. dens.)	1.29	0.00	0.00	N/A	This study
1999	Mat&Pam	Pushnet (ave. dens.)	0.09	0.01	0.04	1.8	This study
1998	Mat	Stationary (#/hr)	0.004	0	0	N/A	This study
1999	Mat	Stationary (#/hr)	0	0	0	N/A	This study

[1] Maurice et al. 1987 reported total counts of egg and larvae (yolksac and post-yolksac combined) for a 4 year sampling period with 1,289 collections.

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Figure 1.1. Extent of ichthyoplankton sampling in 1997-1999 using bongo net, pushnet and stationary net gear for collection within the Mattaponi and Pamunkey rivers. River kilometer increments are denoted as the number of kilometers from the mouth of the York River.

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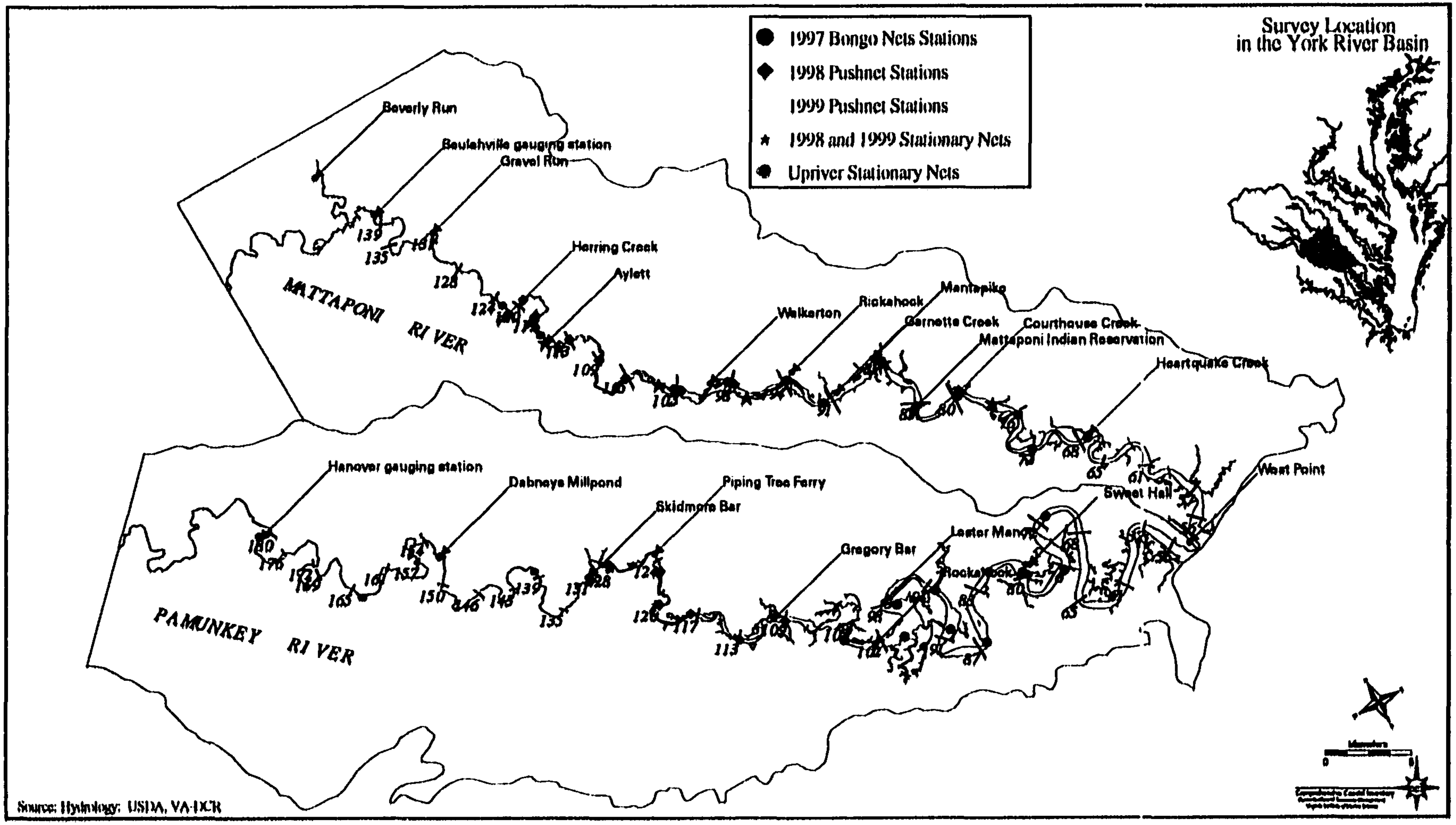

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Figure 1.2. American shad egg density and distributions for 1997-1999 bongo and pushnet collections. Stations are denoted as the distance in kilometers that the station is from the mouth of the York River.

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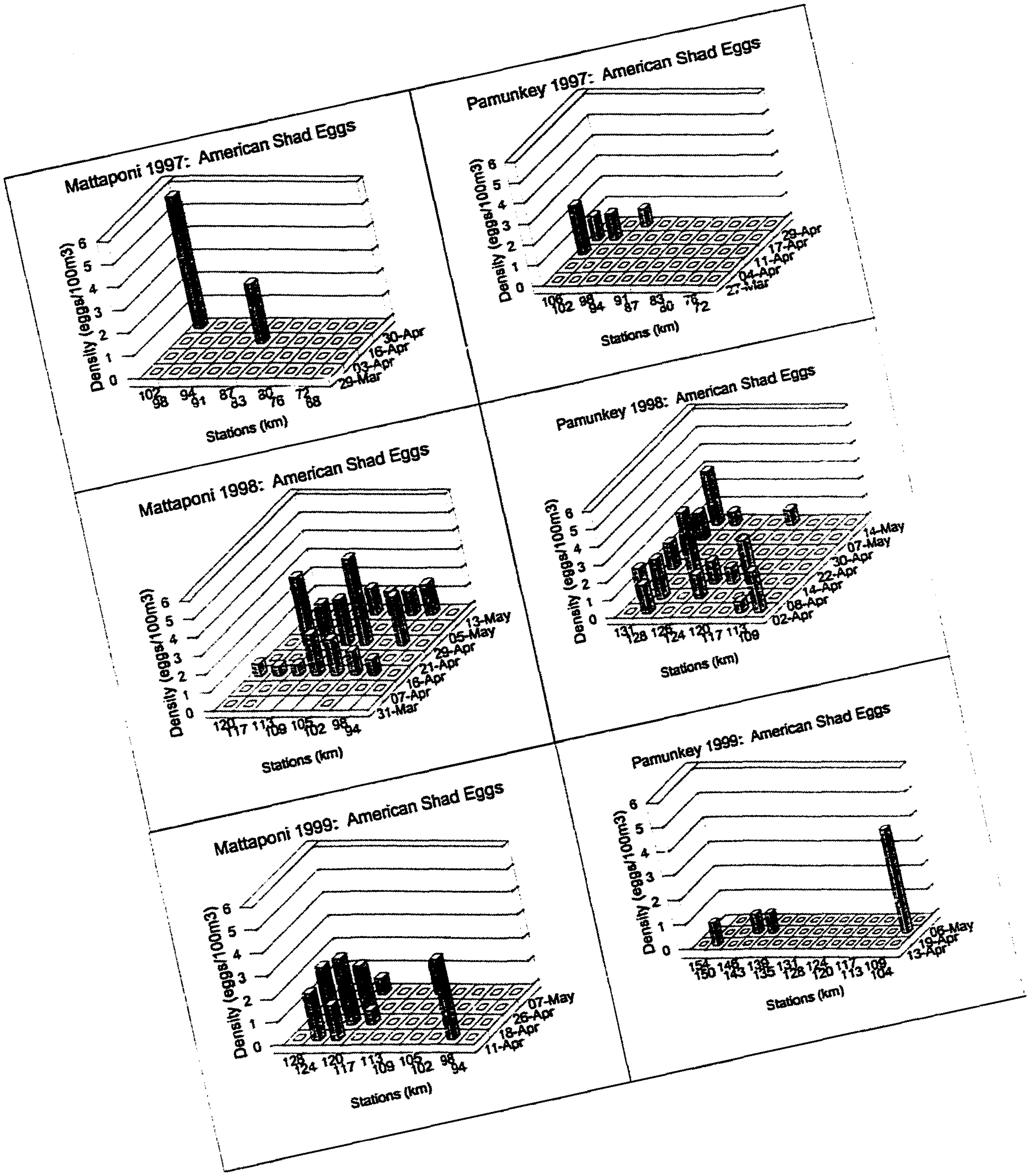

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Figure 1.3. American shad larval density and distributions for 1997-1999 bongo and pushnet collections. Stations are denoted as the distance in kilometers that the station is from the mouth of the York River.

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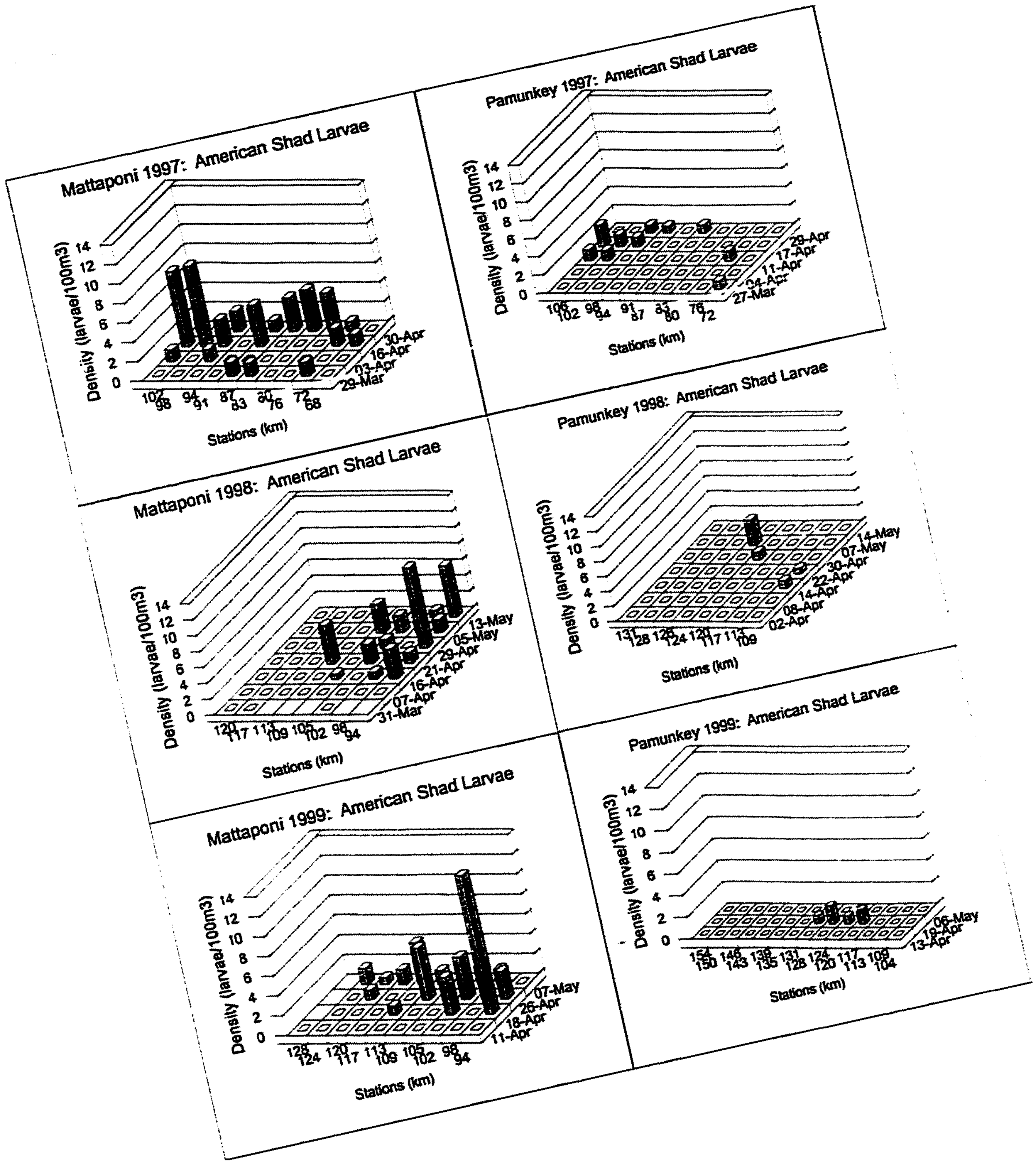

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Figure 1.4. American shad egg and larval counts and distributions from the Mattaponi River stationary net collections for 1998-1999. Stations are denoted as the distance in kilometers that the station is from the mouth of the York River. No American shad larvae were collected in 1999 stationary net collections. Not shown on the graphs were collections of shad eggs in two locations upriver of regularly sampled locations: Dabney's Millpond (km 152, Pamunkey River) and Herring Creek (km 122, Mattaponi River).

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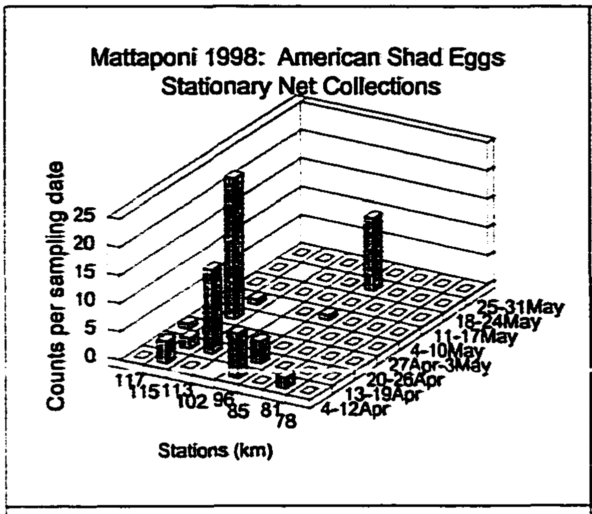

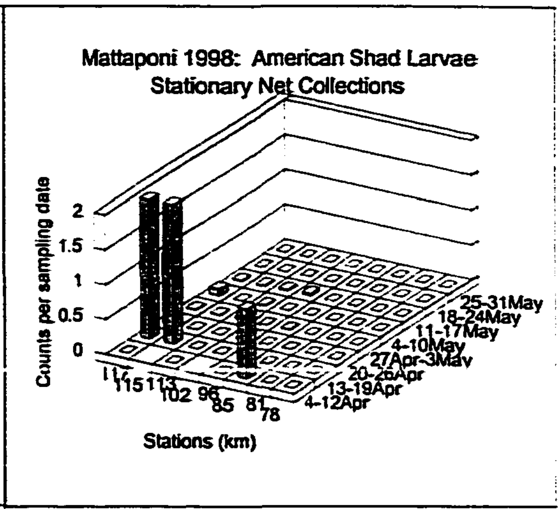

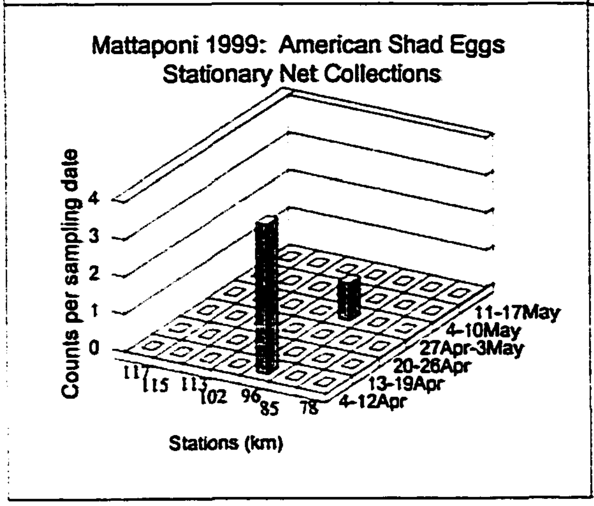

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Figure 1.5. Striped bass egg density and distributions for 1997-1999 bongo and pushnet collections. Stations are denoted as the distance in kilometers that the station is from the mouth of the York River. In 1998, no striped bass eggs were collected on the Mattaponi River. Not differences in scaling on the y-axis.

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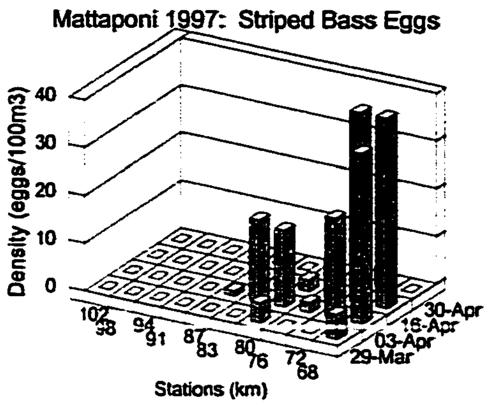

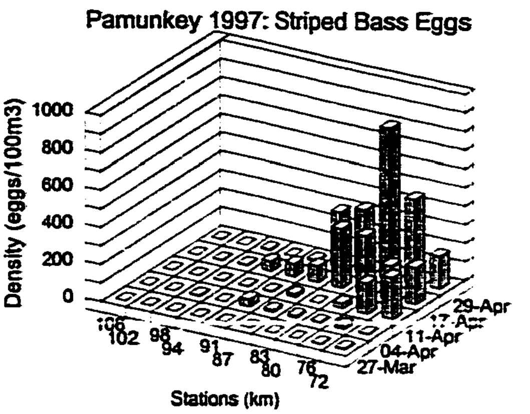

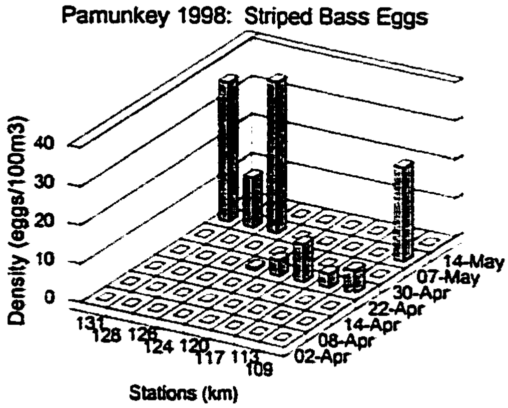

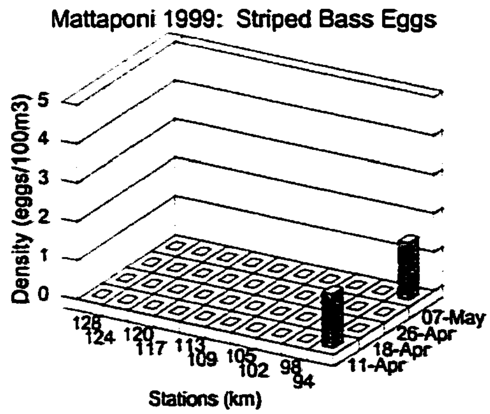

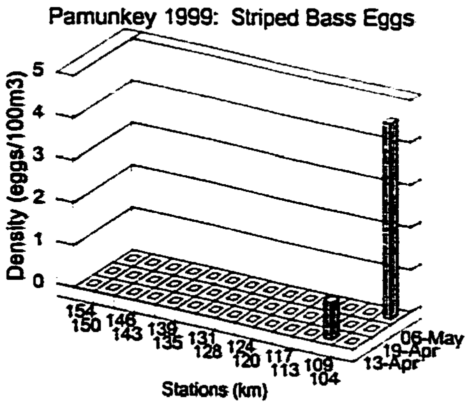

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Figure 1.6. Striped bass larval density and distributions for 1997-1999 bongo and pushnet collections. Stations are denoted as the distance in kilometers that the station is from the mouth of York River. In 1998, no striped bass larvae were collected in either river. Note differences in scaling on the y-axis.

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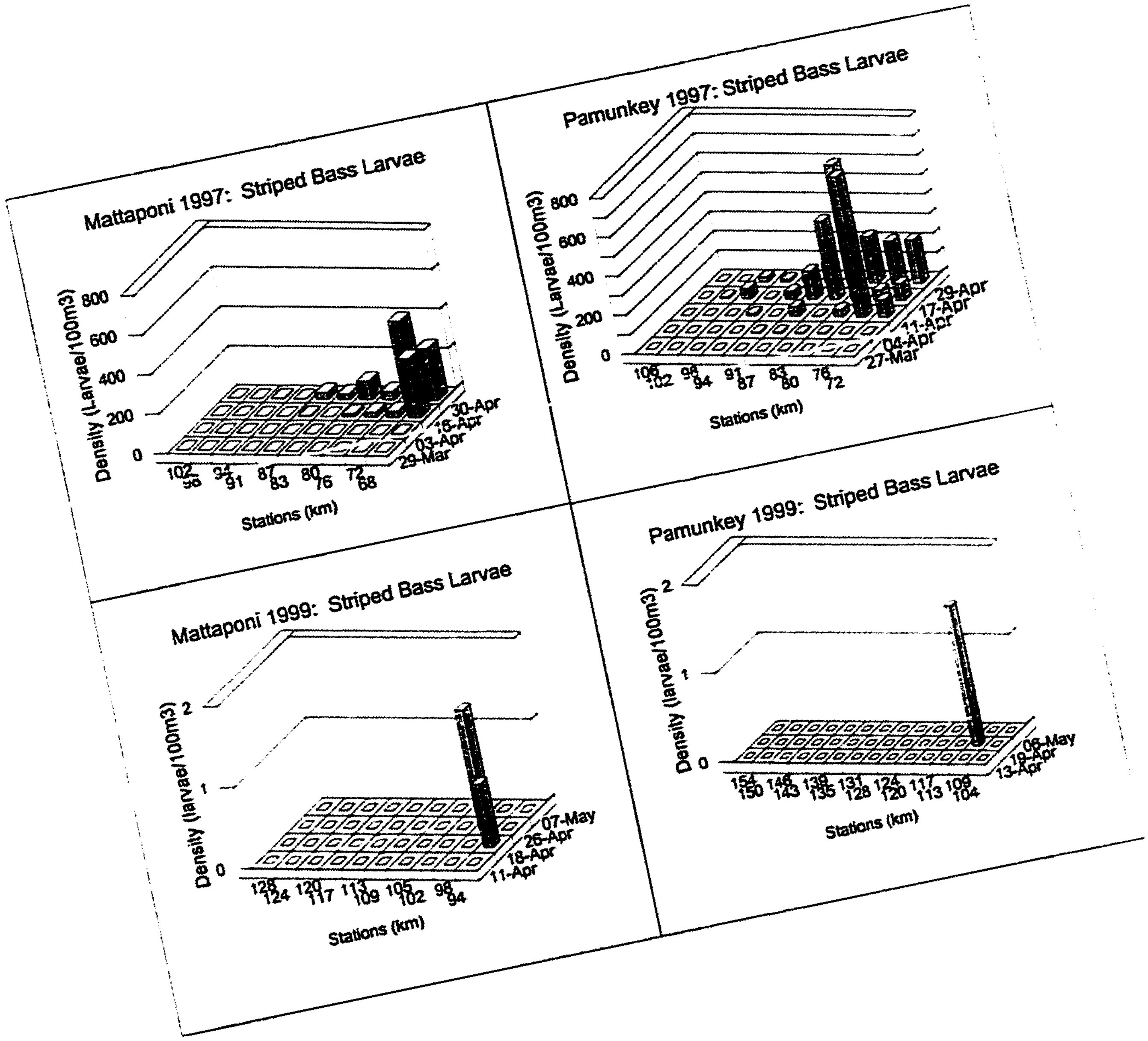

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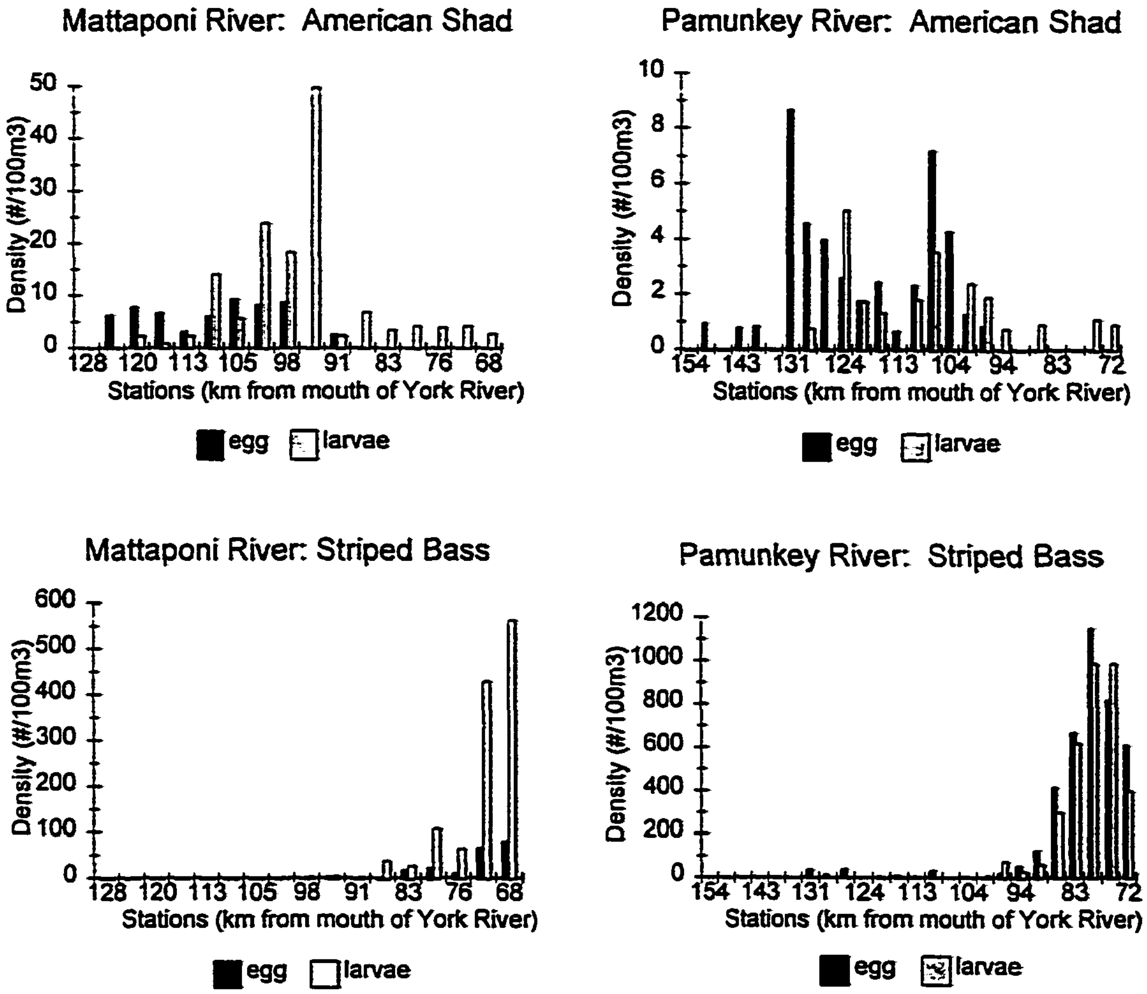

Figure 1.7. Total average American shad and striped bass density distinguished by river, species and life stage for the 1997-1999 bongo and pushnet collections. Note differences in scaling on the y-axis.

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Figure 1.8a. Map depicting reaches on the Mattaponi River where American shad and striped bass eggs were collected. Categories delineated are 1) areas where only American shad eggs were collected, 2) areas where only striped bass eggs were collected, and 3) areas where both American shad and striped bass eggs were collected.

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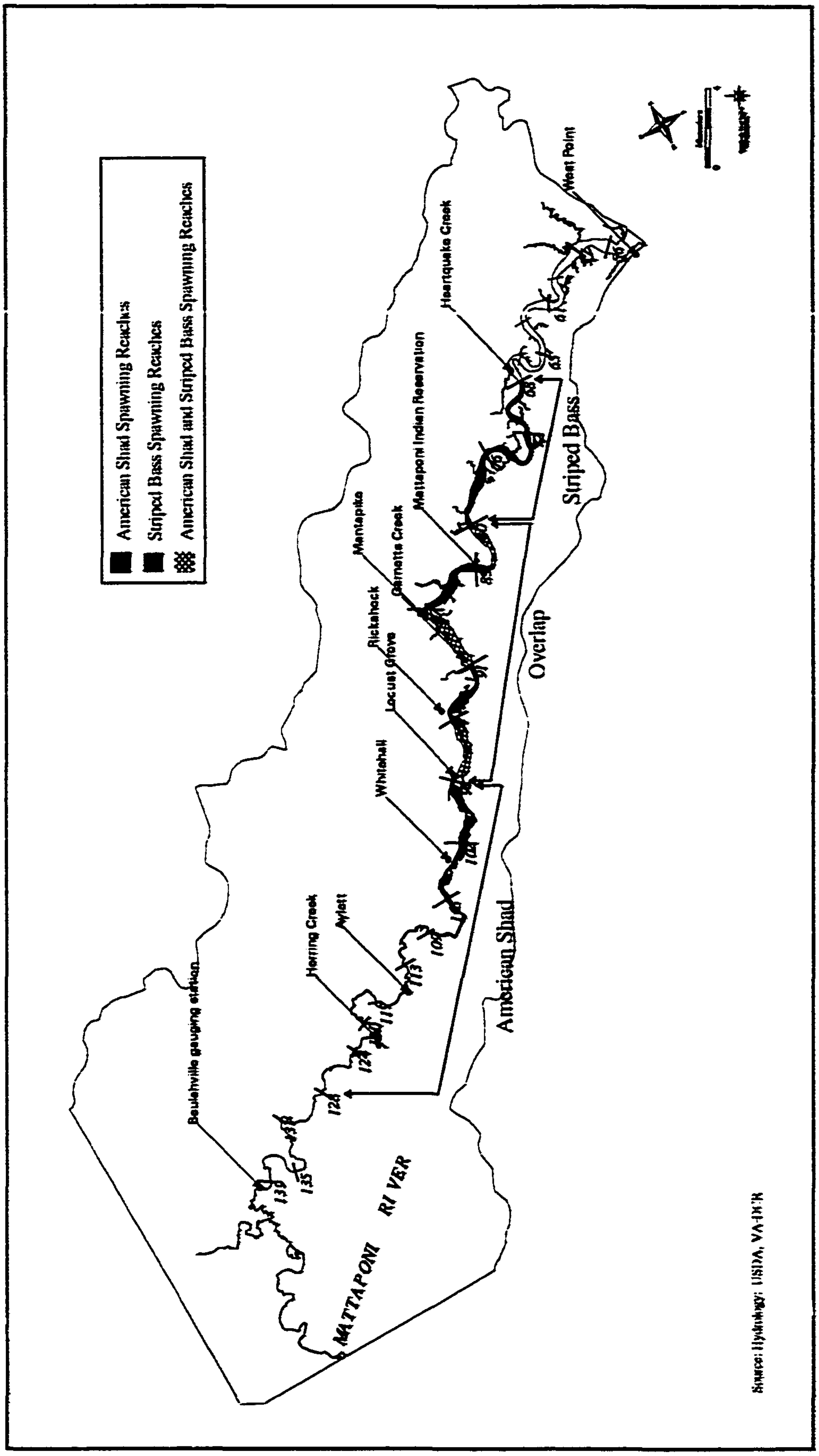

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Figure 1.8b. Map depicting reaches on the Pamunkey River where American shad and striped bass eggs were collected. Categories delineated are 1) areas where only American shad eggs were collected, 2) areas where only striped bass eggs were collected, and 3) areas where both American shad and striped bass eggs were collected.

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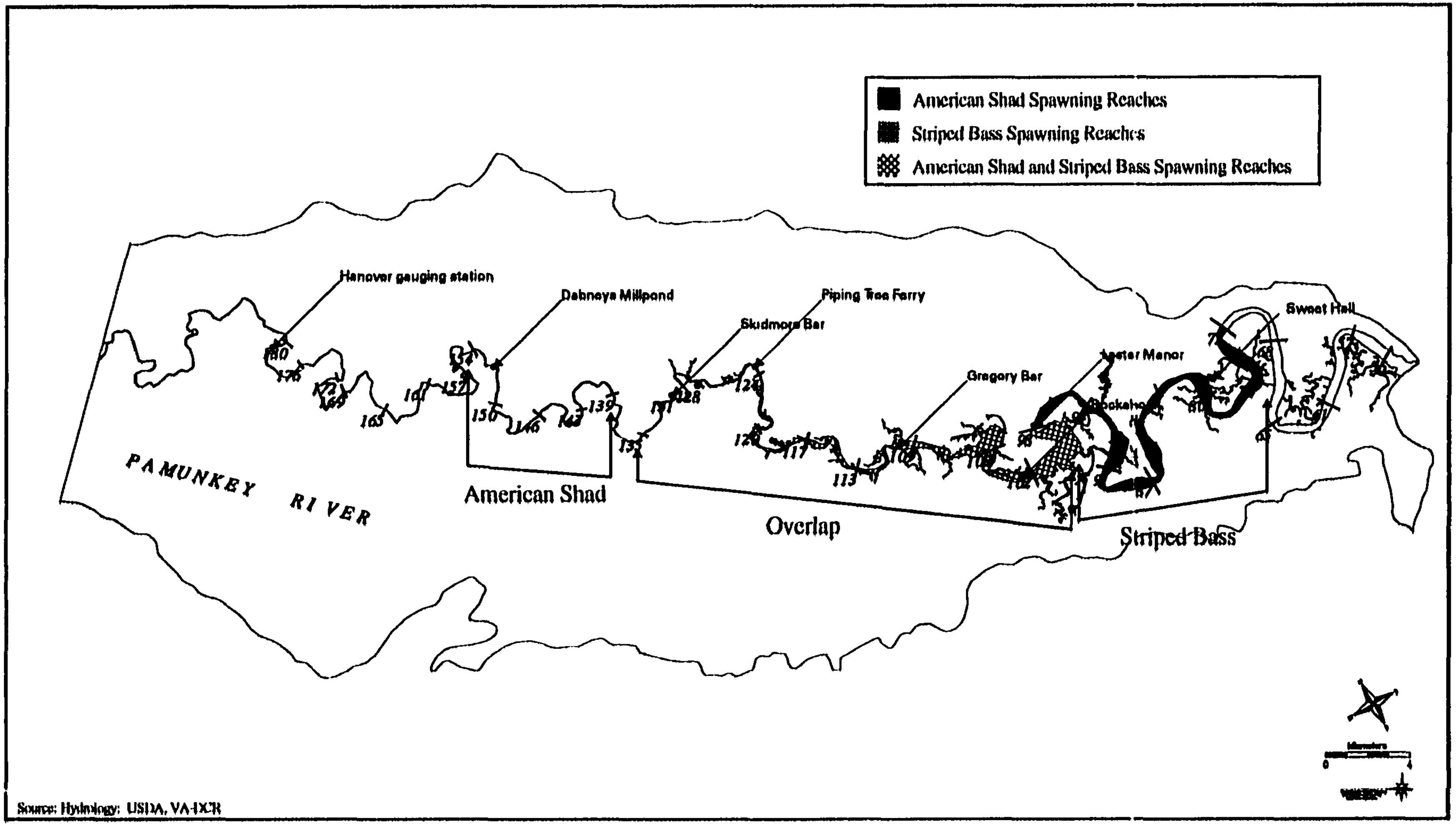

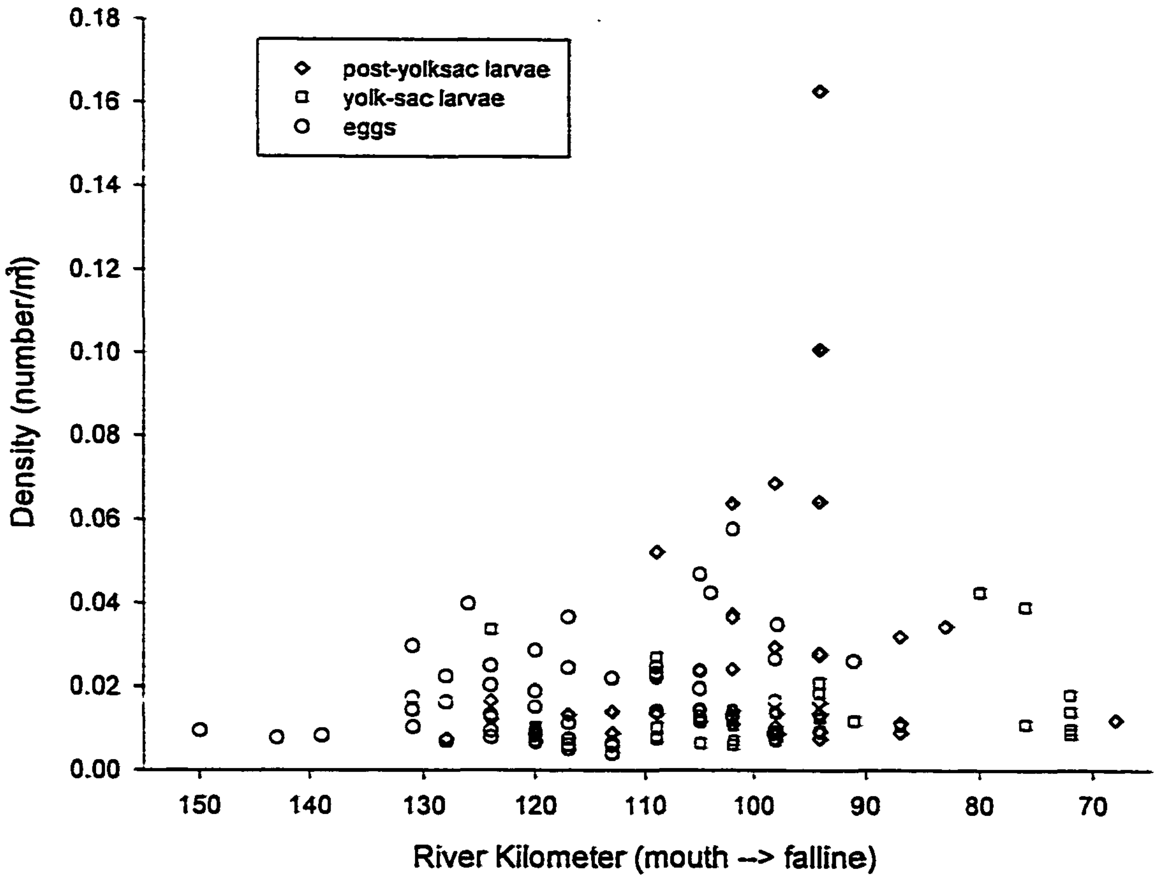

Figure 1.9. Density of American shad eggs, yolksac and post-yolksac larvae in association with location in the Mattaponi and Pamunkey rivers (1997-1999). 'River kilometer' is equal to the distance in kilometers from the mouth of the York River. o = eggs, □ = yolk-sac larvae, ◆ = post-yolksac larvae.

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Chapter 2

Description of Habitat Suitability Index Models for American shad incorporating hydrographic, physical habitat and land use parameters

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Abstract

Habitat suitability index (HSI) models have an important application in the evaluation of species-habitat relationships. While acknowledging model limitations, HSI models allow for the general evaluation of habitat requirements of a species and identify scientific information needs. HSI models for several hydrographic parameters thought to impact American shad were originally developed in the 1980s. During the next decade, the HSI models were evaluated and adjusted when necessary for specific use in the Delaware River. Neither of these analyses modeled landscape parameters, however. Shoreline and land use parameters have the potential to influence the physical habitat of riverine systems that may ultimately affect shad production. Based on an extensive literature search and the above studies, habitat suitability index models were developed that describe potential influences on American shad production in the Mattaponi and Pamunkey rivers. Separately, hydrographic, physical habitat, and shoreline/land use parameters were scaled to denote suitability indices (SI) ranging from 0 (suboptimal) to 1 (optimal) for the life stages of shad that utilize riverine environments. The rationale for each scale is thoroughly described and supported based on a literature review. Deficiencies in available data for shad included land use and physical habitat parameters, and in these cases HSI models were hypothesized based on scientific literature of similar systems or species.

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Introduction

Habitat Suitability Index (HSI) models can be valuable management tools to enhance the understanding of species-habitat relationships, aid in impact assessment and habitat management decisions. HSI models, originally developed in the 1970s and 80s, are defined as " the numerical index that represents the capacity of a given habitat to support a selected fish or wildlife species" (USFWS 1981). Several types of HSI models were developed including: 1) category-one suitability curves which are indices based on literature or surveys of those with knowledge of a fishery, 2) category-two utilization curves which incorporate frequency analyses of field data and 3) preference curves that are corrected for environmental bias by accounting for the relative amount of different habitat types in the study area (Stier and Crance 1985; Crance 1987). Category-one curves are the most commonly used due to limited knowledge on the habitat requirements of many species. Category-two and three curves are more detailed and require more intensive investigation than category-one curves. When data are limited, category-one curves may be used as a first approach to evaluating the habitat requirements of a species, as well as identify scientific information needs.

Several limitations are apparent for the above models and should be addressed. One of these is the narrowness of site applicability. Recent attempts to expand the limited application of habitat models have included basin-wide analysis which incorporates landscape patterns, as well as physical stream parameters (Osbourne and Wiley 1988; Richards and Host 1994). Additional limitations of HSI models noted by Rickers et al. (1995) include: lack of data over large areas to characterize habitat and lack of detail or resolution for planning purposes, such as assessing changes over temporal or spatial

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scales. Spatial analysis tools, such as geographic information systems, can mitigate the latter, as well as the problem of integration of several spatial parameters into one model, but it cannot eliminate the lack of data or site-specificity of some models.

The HSI models for American shad (*Alosa sapidissima*) were first developed for spawning adults, eggs and larvae in riverine environments by Stier and Crance (1985), and then modified for the Delaware River system by Ross et al. (1993). These original models assumed that water temperature during spawning and development and current velocity during spawning were the most important parameters. Other variables such as depth, substrate and cover were considered insignificant influences on habitat use (Stier and Crance 1985). In the Delaware River system, these assumptions were adjusted since depth was found to positively influence postlarval densities (Ross et al. 1993). None of these models addressed landscape parameters, however.

Shoreline and land use parameters have the potential to influence the physical habitat of riverine systems and may ultimately affect shad production. Natural buffer zones provide several functions: filtering sediment, providing shade, large woody debris and overall protection of fish habitat (Murphy 1995). These functions in turn influence physiochemical habitat factors described by Beschta (1991): 1) channel roughness and energy dissipation, 2) water temperature, 3) nutrient cycling, 4) large woody debris loading, 5) bank stability, 6) sediment deposition and 7) water storage. To model potential habitat influences on American shad within the York River, Virginia, a survey

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of scientific literature was completed and HSI models were described for hydrographic, physical habitat and land use parameters.

Methods

Habitat suitability index models that describe potential influences on American shad production in the Mattaponi and Pamunkey rivers were developed. Separately, hydrographic, physical habitat, and shoreline/land use parameters were scaled to denote suitability indices (SI) ranging from 0 (suboptimal) to 1 (optimal) for the life stages of shad that utilize riverine environments. Optimal ranges are where shad growth and feeding are presumed the highest and mortality is reduced. Unsuitable ranges are where the expectation is reduced growth and feeding rates, increased mortality rates, and eventual death after prolonged exposure. Each parameter and corresponding suitability index are applicable to the egg and larval life stages. unless noted. Deficiencies in available data are noted and habitat suitability indices are hypothesized when necessary.

To determine the potential impact of land use or riparian features on shad populations, optimal and unsuitable ranges were often extracted from research that estimated indices of biological integrity (IBI). Biological integrity is commonly defined as "the ability to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity and functional organization comparable to those of natural habitats within a region" (Karr and Dudley 1981). Researchers often apply IBI to measure the integrity of a system for biota, and the threshold amount of a particular land use that may impact a system can be obtained from this application.

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Results and Discussion

Habitat Suitability Index Model Description

Hydrographic Parameters

Temperature (°C)

SI	Range
1	14-24.5
0	< 8; > 27

Numerous researchers assert the importance of water temperature in determining spawning runs, migration patterns and larval development of anadromous fishes. Temperature fluctuations impact the timing and location of American shad migrations, spawning, and the subsequent production of eggs, as well as larval growth, survival, and food supply (Leggett and Whitney 1972; Leggett 1976; Crecco and Savoy 1987a).

Determination of lower and upper temperature limits is based on the ability of American shad to not only survive, but also to grow and reproduce. Most of the literature is in agreement, within a few degrees, about the optimum temperature ranges for shad. The scale developed is based on the literature with an emphasis on the most current studies (Ross et al. 1993; Stier and Crance 1985), and studies in close proximity to the York River (Rice 1878; Ryder 1882; Massmann 1952; Bradford et al. 1968). Lower and upper temperature limits (8°C and 25°C) for eggs and larvae proposed by Stier and Crance (1985) were generally verified by Ross et al. (1993). One exception noted by Ross et al. (1993) was presence of postlarval stages at temperatures exceeding 25°C, thus the upper limit was extended to 27°C to accommodate this life stage. Specific studies within the Chesapeake Bay region denoted by life stage are referenced below.

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Spawning Adults

Massmann and Pacheo (1957) examined catch records for temperature effects during shad runs on the York River in 1953 through 1956. In > 4.0°C waters, shad entered the York River with peak numbers occurring in April at temperatures of approximately 14°C, at higher temperatures the catches declined. Likewise, Walburg and Nichols (1967) observed that egg deposition can occur in waters of 8 to 26°C, but most spawning in the Chesapeake Bay has been observed at temperatures between 12 and 21°C, typically between mid-February/early March through early June.

Eggs and Larvae

Leim (1924) observed that the rate of shad egg development was related to temperature. He determined the optimum temperature for egg development to be 17°C based on lab studies. Although no viable larvae developed from incubated shad eggs obtained from Canadian waters at 22°C, Leim (1924) noted that shad from the southern end of their range, such as the Chesapeake Bay, may be able to tolerate higher temperatures than 22°C. His comments were in reference to prior studies within the Chesapeake Bay (Rice 1878; Ryder 1882), which reported hatching at 26.8°C, but the larvae were less hardy than those from lower temperatures.

More recent studies within the Chesapeake Bay support lower and upper temperature limits of 8 and 27°C. Bradford et al. (1968) noted that in the Susquehanna, temperatures below 8-10°C and above 27°C are unsuitable because embryo development either ceases

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or abnormalities appear in the resulting larvae. In the Pamunkey River, Massmann (1952) collected shad eggs at temperatures of 6.4 to 21.9°C. Only a few eggs were taken at 9.2°C and eggs were not taken in abundance until temperatures were 14°C or greater. Table 2.1 summaries temperature range data reported for American shad.

Dissolved Oxygen (mg/L)	
SI	Range
1	> 5.0
0	< 4.0

Dissolved oxygen (DO) level represents those necessary to promote survival, growth, reproduction and successful development of early life stages. DO levels are not strictly based on death, other responses such as equilibrium loss are considered.

Based on a literature review, Klauda et al. (1991) stated that DO levels of 4 mg/L are required in shad spawning areas. This was supported by observations of increased spawning of American shad in the Delaware River coincident with improved DO concentrations in the tidal portion (Maurice et al. 1987). Chittenden (1973) reported that about "4.0 mg/L seems to be the minimum permissible daily oxygen level in spawning areas" in the Delaware River. Jessop (1975) supported Chittenden's findings when he observed that DO must be at least 4 - 5 mg/L in headponds through which shad pass in their migration.

Although few specific egg and larval DO tolerance or optima data were available in the literature, observations were made by authors regarding the presence or absence of eggs and larvae in certain DO conditions. Marcy (1976) noted that in the Connecticut River

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Table 2.1. Reported temperature ranges for American shad on the Atlantic Coast.

Location	Temperature range	Optimal range	Life stage	Reference
Potomac River	8 to 24.5°C	12.0 to 21.0°C	All	MacDonald (1887)
Canadian waters	N/A	15.5 to 26.5°C	eggs and larvae	Leim (1924)
Chesapeake Bay	8 to 26°C	12 to 21°C	Spawning adults and eggs	Walburg and Nichols (1967)
Susquehanna River	10 to 27°C	N/A	eggs and larvae	Bradford et al. (1968)
Upper Ches. Bay	10 to 25°C	N/A	larvae and juveniles	Chittenden (1969)
Atlantic Ocean and tributaries	N/A	13 to 18°C	Adults	Leggett and Whitney (1972)
N/A	10 to 30°C	15 to 25°C	Developmental stages	Stier and Crance (1985)
N/A	8 to 26°C	14 to 20°C	spawning adults	Stier and Crance (1985)
Delaware River		14.0 to 24.5°C	spawning adults	Ross et al. 1993
Delaware River	8.2 to 26.6°C (eggs) 13.0 to 26.2°C (yolksac larvae)	15 to 25°C	eggs and yolksac larvae	Ross et al. 1993
Delaware River	13°C to ?	15°C to ?	Postlarvae	Ross et al. 1993
Delaware River	17°C to ?	19.5 to 24.5°C	Juveniles	Ross et al. 1993

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shad eggs were absent where the DO concentrations were lower than 5 mg/L. The LC50 for shad eggs was observed at 2.0 to 2.5 mg/L in the Connecticut River and 3.5 mg/L in the Columbia River with 4.0 mg/L required for normal hatching (Bradford 1968). Thus, DO values of 5.0 mg/l or greater are considered optimal for shad spawning and nursery reaches.

<u>pH</u>

SI	Range
1	6.0 – 9.9
0	≤ 5.7; ≥ 10.0

Suitability levels of pH were extrapolated for spawning adults from egg and larval tolerance studies, since no information was available for this specific life stage. Leim (1924) performed one of the few studies on pH tolerances of young shad. During lab studies, pH values between 6.0 to 9.0 caused no unfavorable effects on hatching and larvae from the Shubenacadie River. At pH levels of 10.0 and above, conditions were unfavorable for egg development and larvae were less active than in less alkaline situations. In a later study, Bradford et al. (1968) observed that a pH of 6.0 was necessary for successful larval hatching to occur. The calculated LC50 for larval hatching was approximately at a pH of 5.5. Further lab studies on yolk-sac larvae indicate that pH levels of 5.7 and 6.2 eventually lead to 100% mortality. Feeding larvae were also observed to have an increased sensitivity to acidic pulses compared to yolk-sac larvae (Klauda et al. 1991). Thus, pH values below 6.0 are suboptimal and those below 5.7 are considered lethal.

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Current velocity (m/s)	
SI	Range
1	0.3-0.7
0	0; > 1.0

Several researchers proposed optimum current velocity ranges of 0.3-0.9 m/s for spawning adults, eggs and larval stages of American shad (Walburg 1960; Walburg and Nichols 1967; Stier and Crance 1985). Ross et al. (1993) modified this range by decreasing the lower and upper limits to 0 m/s and 0.7 m/s, respectively. Shad eggs were generally collected in current speeds of 0.3-0.45 m/s in St. Johns River during ichthyoplankton surveys in 1969-1970 (Williams and Bruger 1972).

Low current velocity areas induce deposition of finer grained sediments and cause abnormally high egg mortalities by suffocation and bacterial infection. Minimum velocities of 0.3 m/s are required to prevent siltation and insure conditions conducive to spawning and incubation of eggs (Williams and Bruger 1972). Persistent velocities exceeding 1.0 m/s are postulated to be too high for retention within the system. In a similar fashion to current velocity, the amount of freshwater discharge can influence the spawning and nursery locations of American shad, and potentially recruitment.

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Freshwater discharge (m^3/s)		
Mattaponi River		**Pamunkey River**
SI	Range	Range
1	20.5-43.7	33.4-71.2
0	> 100	>150

Marcy (1976) used a model including temperature, river discharge and spawning population numbers as variables to predict juvenile production. He observed high flows and low temperatures during a spawning season prolong the development of the eggs and reduce their survival. Eggs have the potential to be swept downstream of the nursery grounds by high flows leading to mortalities. High flow values in June (578-892 m^3/s) were correlated with the lowest estimated adult shad population, while low flow values (244-306 m^3/s) correlated with the highest estimated shad population based on juvenile catches in the Connecticut River.

Crecco and Savoy (1987a) advanced Marcy's model by examining match and mismatch factors. They stated that interannual fluctuations in precipitation and river flow can influence the river temperature gradient and, perhaps, the synchrony between the production of larvae, their food supply and their predators. They further remarked that episodic fluctuations in May and June river flows greatly effet larval survival rates, leading to a wide scatter of recruitment values about the stock-recruitment curve. This was postulated to be due to reduced availability of zooplankton by reducing patchiness and visibility to first-feeding larval shad from increased turbidity produced by high river flows. High river flows are associated with a reduction in water temperature and transparency, the advection of larvae from preferred habitat and dissipation of microscale patches of river zooplankton (Beach 1960). Crecco and Savoy (1985) carry this

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argument a step further by relating these effects to lower growth and higher mortality rates of first-feeding larvae. Larval and juvenile American shad will forage within "specific littoral habitats such as eddies and backwater areas where river flow is greatly reduced" (Crecco and Savoy 1987b), and these habitats would be disturbed by high river flows.

Discharge increases approximately linearly with an increase in watershed size (Leopold 1994). Therefore, an estimate of comparable discharge levels in the Mattaponi and Pamunkey River can be derived from the Connecticut River. The Connecticut River watershed is approximately 11.9 and 7.3 times greater than the Mattaponi and Pamunkey Rivers, respectively. Thus, June discharge reported by Marcy (1976) to be optimal for shad recruitment in the Connecticut River (244-520 m^3/s) is the equivalent of approximately 33.4-71.2 m^3/s in the Pamunkey River, and 20.5-43.7 m^3/s in the Mattaponi River for May. High flows that may induce low juvenile recruitment are estimated at 80.3-123.9 m^3/s (Pamunkey River) and 48.6-75.0 m^3/s (Mattaponi River). Thus, unsuitable high flow levels were hypothesized to be greater than 150 m^3/s and 100 m^3/s for the Pamunkey and Mattaponi rivers, respectively. It is also possible that extreme low flow would adversely affect juvenile recruitment by diminishing advection of eggs and larvae to nursery grounds. More research on the impact of extreme low flow on recruitment is necessary for accurate habitat suitability assessment.

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Salinity (ppt) (eggs and larvae)

SI	Range
1	0 - 7.5
0	> 7.5

Spawning usually occurs in tidal freshwater regions of tributaries (Chittenden 1976), although Leim (1924) observed young shad in the nontidal regions of the Shubenacadie River. Likewise, in the Chesapeake Bay tributaries, shad have historically ascended farther upriver than at present. Prior to dam building in the James River, large numbers of shad traveled over 500km (335 miles) from the Chesapeake Bay into the Jackson and Cowpasture tributaries (Mansueti and Kolb 1953). Although spawning occurs in freshwater, shad appear to be very tolerant of estuarine salinities, and it is thought that this tolerance begins in early life stages (Leim 1924; Limburg and Ross 1995). Leim (1924) verified that eggs and larvae were primarily observed at salinities between 0 and 7.63 ppt, usually 0 ppt. He suggested that shad eggs and larvae can tolerate brackish water with salinity as high as 15 ppt. Lab studies at 17 °C varying salinities with eggs and larvae indicated that at a salinity of 7.5 ppt, larvae were vigorous, frequently swimming up in the water for several days after the yolk was absorbed. Salinity of 15 ppt resulted in earlier deaths of larvae and shorter periods of activity than 7.5 ppt. Furthermore, at salinity of 22.5 ppt egg deaths occurred before extensive development, or the egg membranes were soft so that hatching was premature. At lower temperatures (12°C) more abnormalities were observed at 15 ppt, indicating that temperature is an influential factor to salinity sensitivities.

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A more recent study by Limburg and Ross (1995) came to different conclusions than Leim (1924). Their experiments indicate that three levels of estuarine salinities (0-1%, 9-11% and 19-20%) did not depress growth rates or induce mortality for larvae from the Delaware River. They concluded that physiological effect of salinity was not the driving ecological factor in the evolution of freshwater spawning for this species. For their lab experiments larvae were transported in 10 ppt, thus larvae sensitive to higher salinity may have been excluded from the final experiments. Because of the lack of definitive salinity thresholds for egg and larval stages and exclusive freshwater spawning by shad, salinities greater than 7.5 ppt were hypothesized to be unsuitable for these life stages as a conservative estimate.

Secchi depth (m)

SI	Range
1	≥ 0.3
0	0

Secchi depth is a measure of the turbidity of a waterbody, which is directly related to the amount of suspended sediment in the water column. Thus, these two parameters were examined for the postulation of the optimal ranges of turbidity for the early life stages of shad. Leim (1924) initially observed that 100 mg/L sediment in rivers didn't seem to harm young shad and may have had some protective value in screening them from the view of their predators. Further experiments by Auld and Schubel (1978) established that shad eggs were not adversely influenced by 1000 mg/L of sediment, while larvae exposed to concentrations greater than 100 mg/L for 96 hours had a high mortality rate. In the Inner Bay of Fundy, where suspended sediment concentrations average 100 mg/L,

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Dadswell et al. (1983) observed increased catch rates of adult shad in high turbidity situations (secchi mean depth = 0.3m), and postulated a preferred light intensity range influenced positioning in the water column. This behavior may occur in juveniles or late larval stages as well and affect their vulnerability to predators. In the Mattaponi and Pamunkey rivers, turbidity may reach 100mg/L, but typical values do not exceed this point, especially in the freshwater portions (Johnson and Belval 1998). Under normal flow conditions in the Mattaponi and Pamunkey rivers, eggs and larvae are not expected to be adversely affected by turbidity. In this study, secchi depth was used as a surrogate for total suspended sediment (TSS), and high turbidity was assumed to occur when secchi depth was less than or equal to 0.3 m (Dadswell et al 1983).

Habitat Features and River morphology

Deadfall (m^2/1000m reach)	
SI	value
1	≥3.8
0	0

Since the 1980s increased examinations of inputs of large woody debris from riparian environments, have revealed its potential importance to stream communities. Large woody debris can act to stabilize the stream and provide heterogeneous habitats. Instream woody debris has been noted to offer benefits to fish populations, including food sources, habitat and cover (Benke et al. 1985). Large boulders or large woody debris could be used as indicators of low velocity and increased roughness of a channel, thus providing high quality fish habitat (Heede and Rinne 1990; Beschta 1991).

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In addition to the biological benefits, stream hydrology, hydrography, nutrients, and organic matter pathways are impacted by the presence or absence of woody debris. Vannote et al. (1980) had predicted that riparian vegetation impacts/inputs in mid to large order streams become minor, and the primary energy sources consist of instream primary production and upstream inputs of fine particulate organic matter. Likewise, Minshall et al. (1983) noted that this prediction is accurate for moderate to high stream gradients (0.09-0.6%). However, Wallace and Benke (1984), found that in low-gradient (0.01-0.02%) middle-order streams (fourth to seventh) of the southeastern Coastal Plain, wood appears to be a major structural feature. They noted that woody debris provide important habitats for macroinvertebrates and sites of high secondary production, as well as afford a relatively stable habitat compared with the unstable fine-grain sandy substrate that characterizes coastal plain systems. Agriculture, deforestation and grazing act to alter structural relationships among physical components of the stream by reducing the amount of woody debris entering the stream and hence the depth, substrate, and current diversity associated with pool and lateral habitat development (Marzolf 1978; Bisson et al. 1987; Schlosser 1991). This may be especially important in low-gradient streams where woody debris may be a primary source of cover for fish as well as a supply of macroinvertebrate prey (Fajen and Layzer 1993).

Fish may use woody debris as a source of food or cover. Larval American shad have been observed to consume chironomid larvae and pupae, trichopteran larvae, cyclopoid copepodites and *Bosmina* spp. (Crecco and Blake 1983; Johnson and Dropkin 1997). Shad larvae were also noted by Crecco and Blake (1983) to feed on less-abundant

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crustaceans and immature insects perhaps due to a larger mean mouth gape than blueback herring (*Alosa aestivalis*), thus lessening interspecific competition. Juvenile shad are thought to be opportunistic with general selection for chironomid larvae and pupae, adult terrestrial insects and trichopterans, with potential shifts in prey items as juvenile size and river location vary (Ross et al. 1997). In the Mattaponi and Pamunkey rivers, Massmann (1963) noted that insects, which rely on deadfall habitats, were the most important prey item for juvenile shad. Additionally, prey of terrestrial origin made up a larger volume of food than aquatic insects. Since major larval and juvenile prey items originated in surrounding wooded areas and utilize deadfall habitats, land-water interactions may be important influences on survival. Wallace and Benke (1984) examined a study site on the Ogeechee River, a Coastal Plain sixth-order stream of the southeastern USA, draining an area of approximately 7000 km^2, that is slightly larger than the Mattaponi and Pamunkey rivers (5^{th} order streams) which drain areas of 2274 km^2 and 3768 km^2, respectively. Other characteristics of Ogeechee River are similar to the Mattaponi and Pamunkey rivers, including low slope, riparian and upland features and discharge. My woody surface area estimates for the Mattaponi and Pamunkey rivers were not directly comparable to Wallace and Benke (1984) due to their inclusion of submerged wood. Therefore, the habitat suitability index for deadfall was hypothesized based on deadfall surface area estimates from 1997-1999 field observations. Deadfall surface area less than 3.8 m^2/1000 m reach was arbitrarily designated as suboptimal (approximately 25% of the available habitat in both rivers was below this value). Those reaches with no available habitat (woody debris) are considered poor habitat (SI=0).

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Sediment Size (categorical)	
SI	Mean Value
1	≥ 2
0	1

The parameter sediment size will not be used to determine habitat suitability as it typically is used in high-gradient streams in which reaches with boulders and large gravels are typical highly rated habitat. Low-gradient streams contain a predominance of fine sediment sizes, thus most habitat would be graded as sub-optimal, if relationships developed for high-gradient systems are applied. However, if a negative impact on eggs is assumed within high silt/clay areas due to the potential for suffocation, than those reaches with a predominance of sand could be rated higher. Walburg and Nichols (1967) stated that spawning over sand and/or gravel substrates is preferred, since there is sufficient water velocity to remove silt deposits. Likewise, Williams and Bruger (1972) reported shad spawning primarily over sandy bottoms free of mud and silt. Sediment size was placed into 3 general categories: 3 = gravel, 2= sand, 1 = mud/silt based on Wentworth classification.

Overhang (categorical)	
SI	Mean Value
1	≥ 0.5
0	0

Overhang is defined in this study as the percentage of river shaded by overhanging vegetation along the banks. The percentages were further grouped into 4 categories: 0 = 0 %, 1 = 1-25%, 2= 25-50%, 3= 50-75% and 4 = 75-100%.

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One function of riparian buffers is shading which may act to moderate rise in stream temperature. Since the Mattaponi and Pamunkey rivers are approximately 5th order streams (Strahler method; Strahler 1963), the effects of shading on the regulation of stream temperature will be minimal. However, % overhang may be used as an indicator of land-water connections. Sediment, nutrients and allochthonous material enter streams via the watershed. Removing nearshore vegetation (overhang) could disrupt aquatic food webs and act to reduce invertebrate and fish production due to the loss of allochthonous energy inputs (Karr and Schlosser 1978).

Sinuosity

SI	Range
1	ratio value > 1.3
0	ratio value = 1

Sinuosity is defined as the ratio of channel length to straight line distance between two points from Platts et al. (1983). The scale ranges from 1 to 4 with a high ratio indicating a very sinuous river channel.

Meanders are thought to lead to the formation of pools and cover in the form of undercut banks. These habitats are typically beneficial to fish. A meandering stream morphology creates a more diverse, heterogeneous habitat and increases the probability that the needs of different life stages of fishes will be met relative to spawning, hatching, rearing and food supply (Heede and Rinne 1990).

Alternatively, channelization tends to increase water velocity and reduce bottom roughness, making the river channel less retentive of organic matter (Decamps 1993).

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This river type is typically void of deep pools that are often preferred habitat of juvenile shad; whereas, strongly sinuous rivers contain pools on the outside of the meanders. Although the majority of riverine habitat studies have been applied to small-river systems due to ease of sampling, large rivers are influenced by similar parameters. Sedell and Beschta (1991) cite Chariton River channel in Missouri as an example of a manipulated large river environment that was straightened and cleared of debris. This channel had 83% less standing crop of fish compared to the unmodified reaches.

Sinuosity may play a lesser role for shad eggs and early larvae as deep pools have not been observed as preferred habitat for these life stages. Zimmer and Bachmann (1978) observed that invertebrate drift density decreased with decreasing sinuosity with a threshold value of approximately 1.3. If prey decreases with decreasing sinuosity than this threshold value may be applicable to feeding shad larvae.

Depth of the river (m)

SI	Range
1	1.5 – 6.1
0	≤ 0.15; ≥ 15.24

Spawning has been observed in rivers at depths of 0.45 to 7 m by several researchers (Mansueti and Kolb 1953; Walburg 1960; Marcy 1976; Kuzmeskus 1977). However, depths of less than 4m are typically denoted as ideal spawning areas. Shad eggs were generally collected at depths of 4 m or less on the St. Johns River, Florida (Williams and Bruger 1972). Likewise, Walburg and Nichols (1967) reported that 40% of shad eggs were collected in water of depths less than 3 m. Jenkins and Burkhead (1994) stated that

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oviposition occurs at water depths usually less than 3 m. Ross et al. (1993) noted that the greatest spawning activity occurred at < 1 m depth in the Delaware River. Massmann (1952) noted that at depths of 1.5 to 6.1 m (5 to 20 ft) five times as many eggs were collected per hour as in deeper waters in the Pamunkey and Mattaponi rivers.

Stier and Crance (1985) summarized the survey results of researchers who indicated a range of 1.5 to 6.1 m (5-20 ft) as an optimal (SI=1) depth for shad egg incubation as well as spawning, larval and juvenile life stages. Depths less than 0.15 m (1.5 ft) and greater than 15.24 m (50 ft) were designated unsuitable (SI=0).

Larval shad may have a broader range of optimal depths, but this is yet unknown. A further complication is the differences in life stage biology of yolk-sac and post larvae. Marcy (1976) noted that yolk-sac larvae are semi-buoyant and remain in deep water. Prior to external feeding, yolk-sac larvae also exhibit an aversion to light. Marcy (1976) further observed that postlarvae were more than twice as abundant in surface waters (0.78/tow) than in deeper waters (0.33/tow), and they became more pelagic in the downstream regions. Due to the dearth of information, optimal depth ranges for the larval stages are listed as the same as eggs until additional data support or refute the range.

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Catchment Land Use and Riparian Land Use

Forested (%)	
SI	Value
1	≥ 80
0	0

Wang et al. (1997) observed a positive and linear relationship between index of biotic integrity (IBI), habitat quality scores and amount of forested land upstream in Wisconsin streams of 2nd-5th order. Sites with 80% or greater forested land use consistently had good IBI scores, while those with 15% or less of forest displayed a wider range of variation in IBI scores.

Schlosser (1991) observed that for large rivers, land use activities primarily affect the heterogeneity of the channel network, as well as the areal extent of the functional interactions between the river and its floodplain. The removal of woody debris, construction of flood-control structures and clearing of riparian zones acts to disconnect the floodplain from the main channel and then reduces habitat heterogeneity and terrestrial inputs. Correl et al. (1992) further distinguished the effects of particular land use areas on the adjacent riverine region of the Rhode River estuary. Riparian forests were able to remove approximately 80% of the nitrate and phosphorus in runoff, as well as about 85% of nitrate in groundwater originating from cropland. Likewise, croplands discharged more nitrogen per hectare in runoff than did forests or pastures. This corresponded to previous observations of lower rates of nutrient release into streams through upland forests than agricultural areas (Correll 1983).

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Decamps (1993) reviewed the reported effects on the flux of materials between rivers and the terrestrial environment. He summarized the work of several authors by presenting a current definition of this concept as a filtering function, which has the potential to remove products such as fertilizers and nitrate transported by groundwater through denitrification. This could reduce eutrophication effects to the stream. The riparian buffer zone has been postulated to aid in the retention of nutrients and carbon during upstream to downstream movement (Decamps 1993).

Urban (%)	
SI	Value
1	≤ 10
0	100%

Urbanization has the potential to impact stream biota by reducing land-water interactions, removing allochthonous energy sources and increasing toxic or wastewater inputs to a stream. Weaver and Garman (1994) showed that 22 years of urban and anthropogenic activities in Tuckahoe Creek watershed had significantly reduced fish abundance and species diversity. Wang et al. (1997) and Limburg and Schmidt (1990) each observed a threshold of 10-20% urban/residential land use, respectively, prior to decline in habitat quality ratings for fish community data (IBI) and anadromous fish density.

Agriculture (%)	
SI	Value
1	≤ 50
0	100

When agricultural land use is less than 50% no apparent impact on IBI scores was observed for Wisconsin streams, however, when agricultural land use exceeded 50%, IBI

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scores decreased linearly (Wang et al. 1997). Some sites with >80% agricultural land use still maintained high IBI scores, but those sites typically had more rocky substrate, were less likely to be channelized and had lower amounts of urban land use than those with low IBI scores.

Agricultural land use is negatively correlated to stream water quality, while forest land use is positively correlated (Osborne and Wiley 1988). Streams draining agriculture watersheds had higher nutrient concentrations than those draining forested watersheds. Additionally, the amount of agricultural land use was correlated with nitrogen and phosphorus concentrations in streams (Omernik 1976). In three Piedmont streams in North Carolina, Lenat and Crawford (1994) observed elevated nutrient concentrations, and suspended-sediment yields and reduced taxa richness of intolerant macroinvertebrates in agricultural and urban catchments in comparison to forested sites.

Agricultural practices have induced sediment impacts on stream biota, such as the deprivation of oxygen by siltation affecting egg survival, and the limiting of larval feeding by reducing zooplankton availability (Fajen and Layzer 1993). Since American shad are broadcast spawners, their mobile eggs are expected to be more tolerant of increased turbidities than species with adhesive eggs, however due to the semi-demersal character of their eggs there is a potential for siltation impact if settling or lodging into bottom structure occurs.

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Nutrient increases could shift a stream system from one that relied on allochthonous inputs to one based on autochthonous matter. Those species of fish that are insectivores may suffer, including larval shad whose diet largely consists of aquatic insects and crustaceans (Massmann 1963; Crecco and Blake 1983; Johnson and Dropkin 1997; Ross et al. 1997).

Erosion (%)

SI	Value
1	< 7%
0	> 90%

Wang et al. (1998) examined low-gradient streams in Wisconsin for relationships between habitat features and fish biotic integrity. The relationship between IBI and bank erosion (the extent of stream banks with bare soil that is susceptible to wind or water erosion) was negative for erosion greater than 7%. Extrapolation of the IBI-erosion relationship elucidated >90% erosion as supporting IBI scores of less than 20. Thus, based on this relationship a HSI was developed with 7% erosion as the threshold value for optimal habitat (SI = 1) and greater than 90% erosion as unsuitable habitat (SI = 0).

Little is known quantitatively about the influence of vegetation on bank stability. It is expected that vegetation with strong and extensive root systems would act to stabilize the banks. Roots can act to bind soil particles and provide resistance to erosion by flowing water (Platts et al. 1987). It is not know whether trees or herbaceous vegetation, or both types together are more effective for bank stabilization (Heede and Rinne 1990). However, streamside trees and large brush are thought to be beneficial to fish

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However, streamside trees and large brush are thought to be beneficial to fish populations, and unvegetated banks can indicate high erosion rates (Heede and Rinne 1990; Beschta 1991). By increasing bank stability, erosion rates decrease thereby leading to reduced turbidity of the rivers. High erosion rates may particularly affect larvae, due to the increased sensitivity of early larval stages to increased siltation and turbidity (Auld and Schubel 1978).

Conclusions

Throughout the literature, the effects of hydrographic parameters on the early life stages of shad were the most thoroughly studied by researchers. Thus, HSI models of water temperature, DO, pH, salinity, and current speed are based on the most extensive research and assumed to be the most accurate. Data deficiencies existed for freshwater discharge and secchi depth (turbidity). Of note is that very little information was taken directly from York River studies, and the assumption that optimal ranges are similar across river systems was inferred. All of the physical habitat suitability indices, except depth, were hypothesized based on other systems and in some cases other species. Likewise, land use parameters were typically derived from index of biotic integrity studies from similar systems, but no direct analysis on the effects of land use type or change on shad were available in the literature. Therefore, future studies on the effects of physical habitat and land use on the riverine life stages of American shad are needed.

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Chapter 3

Macroscale assessment of American shad spawning and nursery habitat in the Mattaponi and Pamunkey Rivers

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Abstract

Variation in habitat suitability can alter the growth and mortality of early life stages of fishes, but is often difficult to measure, quantify and apply to the entire system. Habitat suitability index (HSI) models were designed and tested, incorporating both proximate riverine parameters and surrounding landscape features, as determinates of optimal American shad (*Alosa sapidissima*) spawning and nursery areas. Shad eggs and larvae were collected in the Mattaponi and Pamunkey rivers, during 1997-1999 as direct evidence of nursery habitat use and indirect evidence of spawning reaches. Hydrographic, physical habitat, shoreline and land use features were examined for associations with presence of egg and larvae. Principal components analyses and logistic regressions indicate the importance of hydrographic parameters (current velocity, dissolved oxygen and depth); physical habitat features (sediment type and deadfall) forested shoreline, and land use features to presence of eggs. Larvae were more dispersed than eggs and distinct habitat associations could not be discerned. Morphological features indicate the presence of three distinct regions along the Mattaponi and Pamunkey river gradients. Presence of eggs is typically associated with upper and mid-river regions, while presence of larvae is dispersed amongst the three regions. The combination of remote sensing and on-site data collection and analyses used in this study may be an effective way to rapidly assess essential fish habitat when data are limited.

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Introduction

The Food and Agricultural Organization of the United Nations (FAO) reported in 1995 that 69% of the world's marine fish stocks are fully to heavily exploited, overexploited, or depleted, and therefore in need of urgent conservation and management. Overfishing aside, fish populations may also suffer reduction in abundance due to habitat loss and degradation. Nontraditional methods of fishery management, such as ecosystem-based and habitat protection, are currently advocated due to increasing evidence of the importance of habitat to fish populations. The reauthorization of the Magnuson-Stevens Act, now termed The Sustainable Fisheries Act (1996), applied new mandates for the National Marine Fisheries Service (NMFS), regional fishery management councils and other federal agencies to identify and protect essential marine and anadromous fish habitat (Magnuson-Stevens Act, 16 U.S.C. 1801 et esq).

Delineation of essential fish habitat (EFH) often incorporates large expanses of habitat, especially in the case of migratory fish. The delineation of large areas may act to hinder the effectiveness of the designation. It would be impossible to completely protect large areas from non-fishing effects and difficult to defend the concept of a zone banning human impact from a zone that encompassed vast coastlines. For example, EFH for anadromous fish include not only coastal waters, but also estuarine and riverine spawning areas, making the elimination of all impacts within the designated EFH infeasible. Nonetheless, EFH delineation is required for all managed species and micro-habitat (cm-m) assessments are insufficient for this purpose. A better approach would include an initial determination of all current and potential habitat use by the species, based on

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fluctuating or restored populations. and subsequent targeting of specific areas for restoration and protection. Therefore, a protocol for EFH designation over a macro-scale (m-km) needs to be developed that is capable of defining important areas for protection.

Embedded in the concept of EFH is the notion that habitat has a potential influence on fishery production. An important step to understanding habitat influences on fishery production is to define the envelope of the habitat where the organism lives, and the ecological factors influencing the habitat and its inhabitants (Odum 1971; Hoss and Thayer 1993). The envelope may include physical, chemical and biological characteristics. Until recently, these characteristics were referenced primarily on a microscale (cm-m), in recognition of the small niche in which an estuarine organism physically is found. However. as noted, the process of managing a species often encompasses large areas rendering a macroscale (m-km) approach more appropriate to quickly and accurately define the habitat quality. With a macroscale watershed approach, not only are proximate (micro-scale) variables considered, but also the influence of landscape features on these proximate habitat variables is examined. Regardless of whether landscape is a driving factor influencing a biotic community, its influence on proximate physical and chemical habitat features will eventually affect the biological component. Thus, if measurable (quantifiable) links can be discerned between landscape features and proximate habitat variables, then a watershed approach becomes possible for management of a community. This approach could cover a larger area with lower time and financial commitment from scientists and managers.

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Habitat suitability index (HSI) models can enhance the understanding of species-habitat relationships and be valuable management tools to aid in impact assessment and habitat management decisions. A limitation of HSI models is the narrowness of site applicability. Attempts to address the limited spatial application of habitat models have involved basin-wide analyses that incorporate landscape patterns, as well as physical stream parameters (Lanka et al. 1987; Osbourne and Wiley 1988; Richards and Host 1994). Although watershed and landscape scale influences on streams had been previously noted (Forman and Godron 1986; Platts and Nelson 1988; Schlosser 1991), methods for spatial assessment of landscapes, as well as digital spatial information have only recently been made accessible (Richards and Host 1994). With increased capabilities of spatial analysis tools and increasing knowledge of linkages between land use practices and stream habitat conditions, the interchangeable use of landscape variables for stream habitat parameters as predictors of habitat quality may be realized. Once links can be made between basin-level features and proximate habitat conditions in the stream, the subsequent effect on biota may be accessed (Rabeni 1992). Moreover, it will become possible to determine the effects of habitat loss and degradation on stream biota due to increasing human development.

A protocol for macro-scale fish habitat assessment that incorporates landscape variables has not been developed for coastal plain systems. Previous habitat studies applied to Pacific coast areas and species, lend support to the possibility of a watershed-level approach to stream management (Lanka et al. 1987; Platts and Nelson 1988; Nelson et al. 1992; Hubert and Kozel 1993; Richards and Host 1994; Keleher and Rahel 1996; Rahel

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et al. 1996; Isaak and Hubert 1997). There are limitations to comparisons between those high-gradient systems and rivers along the Atlantic coastal plain. However, the methods of prior studies may be used as a template to be adjusted for coastal plain systems and species.

Within coastal plain systems, American shad (*Alosa sapidissima*), an anadromous clupeid, is a prime example of a species affected by loss and degradation of habitat. Declines in East Coast stocks attributed to habitat loss and flow alterations have led to moratoria in some areas (Mansueti and Kolb 1953; Walburg and Nichols 1967; Carlson 1968; ASMFC 1999). The shad fishery peaked in the Chesapeake Bay in the late 1800s and then declined after the turn of the century (Mansueti and Kolb 1953). As stocks continued to decline in the Chesapeake Bay region during the past few decades, probably due to overfishing, habitat degradation and blockage of spawning runs, the in-river fishery was finally closed for shad in Maryland (1980) and Virginia (1994). In Virginia, in addition to moratoria, fish passageways are opening historic spawning grounds on the James and Rappahannock rivers, and hatchery efforts are taking place on the James and York River systems.

With restoration attempts underway in Virginia, the questions become what is essential shad spawning and nursery habitat and how can it be characterized over a large scale? This study addresses these questions for the York River, a coastal plain system that currently has the largest spawning runs of shad in Virginia (although historically low). Identification and protection of potential spawning and nursery areas for American shad

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is an important component of future rational fisheries management. Water quality, physical elements, and surrounding landscape are integral components of shad habitat. For broadcast spawners with planktonic larvae, such as American shad, chemical and physical parameters of the water column may be the primary influences on the early life stages. However, in-stream and surrounding terrestrial structural habitats, can influence chemical and physical parameters within the river thus altering fish production. This occurs when physical attributes of the environment affect mortality and growth, vital parameters that control biomass in a cohort.

Habitat suitability index (HSI) models were developed that discriminate optimal from unsuitable spawning and nursery areas for American shad in the Pamunkey and Mattaponi rivers, tributaries of the York River, Virginia where shad spawning occurs. Previous HSI models developed for the early life stages of American shad incorporated microscale measurements of hydrographic parameters, such as temperature, salinity and water velocity. The proposed models in this study include hydrographic parameters and expand upon previous models with the addition of physical habitat, and shoreline/landscape features in a macroscale watershed approach. Associations between habitat features and American shad eggs and larvae in the Mattaponi and Pamunkey rivers were then determined for verification and modification of the developed HSI models. This was a three step process: 1) collections of ichthyoplankton along the longitudinal axes of the Mattaponi and Pamunkey rivers 2) evaluation of habitat for the area of collection and 3) quantitative comparisons of the presence/absence of eggs and larvae with habitat evaluation.

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Methods

Ichthyoplankton Collections

Presence/absence data of American shad eggs and larvae were obtained from ichthyoplankton surveys (March-May, 1997-1999) conducted in the Mattaponi and Pamunkey rivers. Sampling encompassed the limits of the brackish water to the fall lines, using the following collection techniques: oblique bongo tows, push-net and stationary net deployments (for detailed methodology see Chapter 1).

Development of Habitat Suitability Index Models

Habitat suitability index (HSI) models were based on an extensive literature review, and developed to describe potential influences on American shad production in the Mattaponi and Pamunkey rivers (see Chapter 2). Hydrographic, physical habitat, and shoreline/landscape parameters were scaled separately to denote suitability indices (SI) ranging from 0 (unsuitable) to 1 (optimal) for the life stages of shad that utilize riverine environments. Optimal ranges are where shad growth and feeding are presumed the highest and mortality is reduced. Unsuitable ranges are where the expectation is reduced growth and feeding rates, increased mortality rates, and eventual death after prolonged exposures. Each parameter and corresponding suitability index are applicable to the egg and larval life stages, unless noted (Table 3.1).

Arc/Info was utilized to create coverages of the habitat ratings and interpolated distribution of the corresponding parameters for each model (Table 3.2). Separate coverages were developed using a compilation of habitat suitability indices for

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hydrographic, physical habitat, shoreline and land use parameters, creating a summed habitat suitability index along the rivers. For hydrographic coverages, two separate ratings were completed. The first rating was completed *a priori* to field evaluation with long-term datasets, and the second rating was completed after field evaluation using data collected in conjunction with ichthyoplankton sampling (1997-1999). Hydrographic data from long-term datasets and 1997-1999 sampling periods were separately averaged and extrapolated to include the entire river lengths. River segments were then coded with the geometric mean score of habitat indices of the measured parameters. Continuous reaches (1000m) along the river gradient were coded separately with physical habitat, shoreline and land use habitat suitability ratings based on data collected in-situ and by remote sensing. Final ratings of habitat were calculated based on the geometric mean of all of the parameters in each model within and adjacent to the respective reach. A cumulative land use habitat rating was also created which used the geometric mean of habitat ratings of all reaches upstream and including the rated reach. Lastly, physical habitat, shoreline and land use ratings were combined for an overall assessment of habitat suitability. Habitat ratings of locations with spawning activity in the rivers were assessed.

Hydrographic HSI model

The hydrographic HSI model (based on available datasets for water temperature, DO, pH, secchi depth and salinity) was applied to the Mattaponi and Pamunkey rivers to create an *a priori* rating of habitat. Parameter values were extracted from datasets comprising several locations along the limits of the tidal influence per river for the time period corresponding to shad spawning in the Chesapeake Bay tributaries (March – May). Microscale hydrographic parameters in the spawning areas were assessed in the field

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during the period of ichthyoplankton sampling for a comparison with the literature-derived ranges. Hydrographic habitat ratings based on averaged field measurements from 1997-1999 (March-May) were compared with *a priori* hydrographic HSI model ratings.

Hydrographic parameters measured during each sampling event were extrapolated along the river gradients based on tidal excursion information. The average tidal excursion per stratum for an ebb cycle (eq. 1) was estimated for the Mattaponi and Pamunkey rivers for the months of April and May, using maximum tidal current amplitudes acquired from tide gauges maintained by the VIMS Physical Science Department along the rivers (Sisson et al. 1997). Median monthly discharge was obtained from United States Geological Survey (USGS) stream gauge stations located approximately at the fall lines of the Pamunkey and Mattaponi rivers. (Hanover station (#01673000); Beulahville station (#01674500), respectively).

Tidal excursion equation (eq. 1):

$Tidal\ Excursion\ (TE) = [(2/\Pi)*u_t + Q/A] * T/2$

where u_t = maximum tidal current (m/s); $2/\Pi * u_t$ = average tidal current (m/s); T/2 = ebb tidal cycle = 6.21hr ; Q = median discharge; $\Pi = 3.14$; and A = cross-sectional area (m^2).

This value was used as a determinate of the most appropriate distance between stations, as well as the extent that hydrographic values, which are dispersed by hydrologic forces, are applicable to a given portion of the river. Hydrographic parameters measured from 1997-1999 included water temperature (°C), dissolved oxygen (mg/L) (DO), pH, and

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secchi depth (m). Current velocity (m/s) was also measured in 1998 and 1999 with a Marsh-McBirney current meter. Dissolved oxygen and water temperature were measured at 1 meter depth intervals with a YSI meter, and median values were calculated. Current velocity and pH were measured once at approximately surface to 1 meter depths.

Physical Habitat HSI model

Several morphological and in-stream habitat factors were chosen as representative descriptors of a low-gradient coastal system, and incorporated into the physical habitat model. Methods of assessment were adjusted from standard high-gradient system metrics to those applicable to low-gradient systems. Typical physical habitat assessments include a measure of slope, width, depth, sinuosity, cover, and sediment type. In these low-gradient systems, there is only a minimal change in slope over the longitudinal distance of the rivers; therefore, slope was not included in this assessment. However, width, depth, sinuosity, overhang cover, deadfall and sediment size were all evaluated. Overhang cover and sediment size metrics were modified for coastal plain systems which have limited riparian overhang and high percentages of fine sediment.

River morphological and structural parameters (Table 3.2) were estimated in 1000 m reaches from the fall lines to West Point on both rivers. Each deadfall counted was a minimum of 0.15 m in diameter and 2 m in length. Using the surface area of a cylinder ($X = \Pi$*diameter*length), the minimum surface area of an individual deadfall was 0.94 m^2. Total surface area per reach segment of 1000 m was calculated by multiplying 0.94 m^2 with the number of deadfall counted. Sinuosity was estimated using shoreline coverages of the York River watershed (United States Department of Agriculture

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(USDA), Virginia Department of Conservation and Recreation (VA-DCR)). Channel length and straight line distance between reaches of a length 20 times the average depth was determined using Arc/Info. Overhang was the visual estimate of the percentage of river shaded by overhanging vegetation, either canopy or bank. Percentages were broadly categorized into 5 metrics: 0, 1-25, 26-50, 51-75 and > 75%. Sediment size was the visual estimate of grain size at three sites per location and then extrapolated along the 1000 m reach length. Size classes included: 3 = gravel, 2 = sand, 1 = mud/silt. Width: depth values were calculated using the average of five measurements per reach of width and depth which was obtained from Arc/Info hydrographic coverages (USDA, VA-DCR), topographic maps and field measurements.

Shoreline/Land Use HSI Model

The shoreline/land use HSI model incorporates shoreline attributes and land use in the surrounding watershed. Riparian zone characteristics were estimated based on the land immediately adjacent to the river. Shoreline attributes of the rivers were coded in the field using a hand-held GeoExplorer GPS unit with a data dictionary that was created to include the following shoreline classifications: 1) forest, 2) scrub-shrub 3) grass/crop 4) residential 5) commercial 6) bare 7) timbered and 8) developed. Some categories contained only small areas of land use, thus this was simplified to three categories: 1) forest (forest and scrub-shrub) 2) grass/crop (grass, bare and timbered) 3) urban (residential, commercial and developed). In addition, erosion was noted as high, low or none throughout the shoreline based on the visual estimate of percentage of stream bank with bare soil susceptible to wind or water erosion (Table 3.2). Line coverages were created from the GPS files using shoreline information and converted to a polygon

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coverage encompassing the reaches. Areas of shoreline features per 1000 m reach were determined using an Arc/Info frequency analysis.

A buffer width of 100 m on each river bank was chosen for determination of land use. This buffer distance was used because a variety of stream functions respond to riparian features within this distance from the stream (Large and Petts 1994; Phillips 1996) and the minimum width of the land-cover data was 30 m X 30 m. Land use percentages per 1000 m reach were calculated from the MRLC (Multi-resolution land use characterization) database from EPA Region III Land Cover Data set, 1996 (Thematic mapper (TM) data from 1992-94 using the combined resources of EPA, USGS and NOAA). In order to determine land use percentages within a designated buffer width, the land use grid coverages were converted to polygon coverages. The land use polygon coverage was than unioned with the hydrologic polygon coverage containing reach demarcations. Next, an Arc/Info frequency analysis was applied to the unioned coverage to extract land use area information for the reaches. The MRLC database classifies land use into fifteen different categories. For this analysis, these categories were combined into three broad classes: forest, agriculture and urban. Percentage of high erosion, urban, agriculture and forest was determined by dividing the area of each variable by the total area per reach and multiplying by 100. All of the Geographic Information System analysis (GIS) was performed on a UNIX SUN SPARC station using ARC/INFO software at the Virginia Institute of Marine Science, Department of Coastal and Ocean Policy, Coastal Inventory Laboratory.

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Sources of Pre-Existing Data Sets

Data were gathered from various sources for use in the GIS analysis. Habitat variables were measured during the 1997-99 sampling period and long-term data were acquired from the Alliance for the Chesapeake Bay and the Virginia Department of Environmental Quality (VDEQ). The Citizen Monitoring Program began a weekly sampling regime for the York River, including the Mattaponi and Pamunkey reaches, in 1992. Records from VDEQ ranged from 1970 to 1997. Topographic maps were used to verify aspects of stream channel morphology including river depth and sinuosity based on the methods of Platts et al. (1983). Surface hydrology that serves as baseline coverages was generated by VIMS, Comprehensive Coastal Inventory and by the U.S. Census Bureau via Topologically Integrated Geographic Encoding and Referencing (TIGER) system files (1991).

Statistical Analysis

Ichthyoplankton density was expressed as number of eggs or larvae in 100 m^3 of water. Presence was defined as any density greater than zero and was denoted with a "1"; absence was any zero value and was denoted with a "0". Scatter plots were generated to illustrate the relationships between habitat parameters and densities of eggs and larvae (1997 – 1999). Habitat suitability indices were superimposed for comparison.

Relationships between the presence/absence of shad eggs and larvae and habitat variables were explored with the ordination technique principal components analysis (PCA) using S-PLUS programming language. PCA reduces the complexity of multivariate data by transforming the original variables to subsets (principal components) of correlated

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variables and can detect structure in the relationships between variables. The PCA applied was the eigenanalysis of the correlation matrix, which standardizes the data measured in different units by dividing by the standard deviation. Analysis was conducted on the hydrographic, physical habitat and shoreline/land use datasets separately. Using the Kaiser criterion (Kaiser 1960) for retention of factors (eigenvalues greater than 1), the first 2 principal components were retained in all cases. Principal component 1 and 2 (PC1 and PC2), were displayed graphically with egg and larval presence/absence superimposed.

PCA correlations were then examined with binary logistic regression in the logit link (Minitab Version 12.0) using shad egg and larvae presence/absence as the dependent variable with principal component 1 and 2 scores as independent variables which represent habitat. Logistic regression is an appropriate statistical test for presence/absence data; it attempts to express the probability that a species is present as a function of the explanatory variables (Jongman et al. 1995). Binary logistic regression uses an iterative-reweighted least squares algorithm to obtain maximum likelihood estimates of the parameters. General results displayed for the logistic regressions consist of estimates and standard errors of the coefficients, z-values, p-values, odds ratio, and a 95% confidence interval for the odds ratio. Additionally, the last log-likelihood from the maximum likelihood iterations is noted with the G statistic. This statistic tests the null hypothesis that all coefficients associated with predictors equal zero.

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Results

Tidal Excursion

The average tidal excursion estimated per stratum for an ebb cycle for the Mattaponi and Pamunkey rivers, with few exceptions did not descend below 3.2 km (Figure 3.1). The highest tidal excursion distances for each month occurred near the fall lines in both rivers. Segments of relatively low tidal excursion were evident at mid-river locations on the Mattaponi River (94-109 km) and Pamunkey River (94-124 km). It is possible that these locations may act as a larval retention zone. Increases in tidal excursion distance were apparent further downstream with declines near the mouths of both rivers (Figure 3.1). Since tidal excursion distance typically remained above 3.2 km, the assumption that water quality measurements may be extrapolated to locations between stations 3.2 km apart is met.

Distribution of American shad eggs and larvae

Examination of morphological parameters indicates the existence of three distinct regions along the river gradients. The Mattaponi and Pamunkey rivers contain a downstream segment with wide, deep channels and extensive marshes (width: 200-600 m; depth: > 5.7 m), a mid-river segment with wide, shallow sandbars (width: 80-600 m; depth: 2-7 m) and a predominately forested upstream segment with shallow, narrow channels (width: < 60 m; depth: < 4 m) (Table 3.3, Figures 3.2-3.3). On the Mattaponi River, the downstream segment is roughly 35 km (53.7-88.8 km, West Point - Mantapike), the mid-river segment is 20 km (88.8-107.3 km, Mantapike – Pointers Landing) and the upstream segment to the fall line is about 33 km (107.3-139 km, Pointers Landing - fall line). On the Pamunkey River, the downstream segment is roughly 55 km (53.7-98.1 km, West

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Point-Lestor Manor), the mid-river segment is about 15 km (98.1-120.3 km, Lestor Manor– Braxton Bar), and the upstream segment to the fall line is about 60 km (120.3-180 km, Braxton Bar - fall line).

Spawning of American shad on both of these rivers predominately occurred within the upper and mid-river segments in 1997-1999. On the Pamunkey River, larval shad typically occupied nursery habitats in mid-river to downstream segments, while in the Mattaponi River larval shad were dispersed throughout all three regions (Figures 3.4 and 3.5). Eggs were collected from km 80-124 and km 98-150 on the Mattaponi and Pamunkey rivers, respectively. Larvae were more dispersed than eggs and found throughout the range of km 68-120 and km 72-128 on the Mattaponi and Pamunkey rivers, respectively. Eggs and larvae were rare in samples and several reasons have been posited, such as low stock sizes relative to historic levels, and spatial or temporal sampling bias (Bilkovic et al. in review).

Habitat analysis

Median values and ranges of hydrographic, physical habitat, and shoreline/land use parameters were similar for the Mattaponi and Pamunkey rivers, thus data from both rivers were combined for analysis (Table 3.4). The median of values was used for comparison to eliminate the effects of outliers or extreme values.

Hydrographic Parameters

Distributions of eggs and larvae exhibited patterns of association with several of the hydrographic parameters examined. A unimodal response curve of densities of eggs and

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larvae to water temperatures was evident. Median water temperatures ranged from 11.8° to 22.0 °C during the sampling periods. The highest densities of American shad eggs and larvae were predominately observed between 14.0° and 19.0 °C. Zero densities were evident in the lower temperatures of 12.0° to 14.0 °C and the highest temperatures of 21.0° to 22.0 °C. In the Mattaponi and Pamunkey rivers, dissolved oxygen median values are higher for eggs (10.8, 10.2 mg/L, respectively), than for yolked larvae (8.2, 9.6, respectively) and postlarvae (8.1, 8.2 mg/L, respectively). All measured DO values in the rivers were well above the lower limit of 5 mg/L necessary for optimal conditions. In both rivers, eggs are typically found in waters with pH between 6.5-7.4, while larvae are scattered throughout the measured range (6.5-9.3). The range of measured secchi depth was 0.2 to 2.0 m. The highest densities of American shad postlarvae were predominately observed between 0.7 and 1.7 m. Eggs and yolked larvae appeared throughout the range of 0.4 and 1.4 m with no apparent pattern (Table 3.4; Figure 3.6).

Shad eggs were observed only at depths less than 5 m, while larvae were distributed from 1-10 m. Current velocity measured at the stations exhibited the broad range of 0 to 1.2 m/s. Egg stages were found within the range of 0.3 to 1.0 m/s. This observation relates to location on the river; upstream sites had higher current velocities, such as the ones where eggs were observed, than downstream sites where eggs were absent. Conversely, yolked and postlarval stages were primarily observed at sites with currents less than 0.5 m/s. This pattern probably resulted from downstream transport of the egg and larval stages throughout development. (Table 3.4; Figure 3.6).

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Physical habitat

Egg presence was primarily evident in reaches where estimates of deadfall surface area were greater than 0.1 m^2. Oppositely, larvae were absent in reaches with estimates of deadfall surface area (> 0.5 m^2). Eggs were located in reaches with designated optimal habitat suitability with only one exception based on a single sampling event, while larvae were often collected in reaches with suboptimal habitat possibly due to downstream transport. For both overhang and sediment size, eggs were distributed throughout the sampled ranges, while larvae were primarily collected in reaches with silt/mud only and less than 1% overhang values. Eggs were typically located in reaches with sinuosity estimates ≤ 1.4, indicative of upstream habitat. Larvae were collected throughout reaches with 1.2 – 1.9 sinuosity estimates. Small peaks in egg and larval density occurred in reaches with a width:depth ratio of 40 or greater, but distinct patterns could not be elucidated with these data (Table 3.4; Figure 3.7).

Shoreline/land use features

Eggs were primarily collected in reaches with greater than 60% forested shoreline and/or land use, and larvae were dispersed throughout the range of sampled forest percentages. The relationships of presence of eggs/larvae to shoreline and land use agriculture differ. Egg and larval densities were highest in reaches with 0% agricultural shoreline, while there was a larger distribution of eggs and larvae throughout reaches 0-35% agricultural land use. There was no distinct pattern with residential (urban) percentages of land use and egg/larval density. Within the Mattaponi and Pamunkey watersheds, 'urban' land use typically indicates residential areas as opposed to intense urban activity. The impact

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of a residential area is expected to be less than larger, urban centers, thus even in reaches with residential shoreline percentages of 30% decreases in egg/larval densities were not evident. There was no distinct pattern for egg or larval distribution throughout the sampled percentages of marsh land use reaches, with the exception that eggs were primarily located in reaches with less than 20% emergent marsh land use, while larvae are largely found in the highest percentages of shoreline marsh. These patterns are most likely indicative of the morphology of the rivers, since marshes dominate in the downstream reaches of both of the rivers below observed spawning reaches but within nursery zones. High erosion percentages were primarily less than 15% throughout the Mattaponi and Pamunkey rivers, and the highest egg and larval densities were found in reaches with 0% values. Of the reaches with 35-45% high erosion, no eggs were collected but larvae were observed (Figure 3.8).

Results for habitat suitability modeling

A priori ratings of reaches with the hydrographic parameters (DO, pH, salinity, temperature and secchi depth) were high for all examined habitat (SI > 0.9) for shad eggs and larvae. Ratings of habitat with hydrographic parameters measured during 1997-99 collections (DO, pH, salinity, temperature, depth, secchi depth, and current velocity) were still high but exhibited greater variability than the *a priori* habitat ratings with suitability ranges of 0.74-0.99 and 0.68-1.0 on the Mattaponi and Pamunkey rivers, respectively (Figures 3.9-3.12). Hydrographic (based on 1997-1999 measurements), physical habitat, and shoreline/land use habitat ratings displayed general trends of decreased suitability with increasing distance from the fall line. Physical habitat ratings, including deadfall, sinuosity, sediment size, overhang and width:depth variables, ranged

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from 0.006 -1.0 and 0.003-1.0 on the Mattaponi and Pamunkey rivers, respectively, and ratings excluding overhang had similar ranges (Figures 3.13 –3.16). Shoreline habitat ratings had a broader range on the Mattaponi River (0.01-1.0) than Pamunkey River (0.43-1.0) with similar average ratings (0.82, 0.98, respectively)(Figures 3.17-3.18). Adjacent land use habitat ratings were within similar ranges on both rivers (0.1-1.0; 0.02-1.0, Mattaponi and Pamunkey rivers, respectively) (Figures 3.19-3.20). Cumulative land use habitat ratings were predominately higher than those of adjacent land use with ranges between 0.76-1.0 for the Mattaponi River and 0.64-0.93 for the Pamunkey River (Figures 3.21-3.22). Combined ratings of physical habitat (excluding overhang), shoreline and land use parameters reiterated the pattern of higher suitability in upstream and mid-river reaches with increased variability in ratings of downstream reaches that was evident in the separate ratings (Figures 3.23-3.24).

PCA And Logistic Regression

Hydrographic PCA

The PCA of hydrographic data (1997-99) indicated eggs typically were associated with areas of shallow depth, high DO and high secchi depth, while larvae were more dispersed with typical occurrences in deeper reaches with high pH and lower DO. PC1 loadings inversely correlated depth with temperature and secchi depth. PC2 loadings inversely correlated DO with depth and pH. Logistic regression indicated that PC1 and PC2 scores were significantly associated with the presence of eggs, while only PC2 scores were significantly regressed with the presence of larvae (Figure 3.25, Tables 3.5-3.6, Appendix I).

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Hydrographic PCA including current velocity

To further characterize the structure of hydrographic features in each river, an additional analysis of 1998-1999 hydrographic data (current velocity was not measured in 1997) incorporating current velocity was completed. Presence of eggs was associated with high DO, shallow depths and high current. Presence of larvae was evident in high water temperature, high secchi depth, and lower DO reaches and again more dispersed than presence of eggs. PC1 loadings inversely correlated DO with water temperature and secchi depth. PC2 loadings inversely correlated current velocity with depth and pH. Logistic regression indicated that PC1 and PC2 scores were significantly associated with presence of eggs, while only PC1 scores were significantly regressed with presence of larvae (Figure 3.25, Tables 3.5-3.6, Appendix I).

Physical habitat PCA

Deadfall, increasing sediment size and overhang are associated parameters and characteristic of upstream reaches. Increasing width:depth ratios occurred at reaches with broad shallow bars, typically mid-river. Increasing number of creeks, and sinuosity were indicative of downstream, marsh reaches. PC1 loadings inversely correlated upstream reaches (deadfall, sediment size and overhang) with mid to downstream reaches (number of creeks, sinuosity and width:depth ratios). PC2 loadings distinguished downstream reaches (marsh, sinuosity) from broad bars (increased width:depth ratios). Presence of eggs was associated with upstream or broad bar reaches, while larvae were more dispersed with association with downstream reaches. Logistic regression indicated that PC1 and PC2 scores were significantly associated with presence of eggs, while only PC1

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scores were significantly regressed with presence of larvae (Figure 3.26, Tables 3.5-3.6, Appendix I).

Shoreline/land use PCA

Respective land use and shoreline features were closely correlated in the PCA. For example, forested shoreline loadings correlated with forested land use loadings. PC1 loadings inversely correlated forested with marsh shoreline/land use, which is indicative of upstream opposed to downstream reaches. PC2 loadings distinguished urban shoreline/land use from marsh reaches. Presence of eggs was associated with forested reaches, while presence of larvae indicated more dispersal within downstream, marsh reaches. Logistic regression indicated that only PC1 scores were significantly associated with presence of eggs and larvae (Figure 3.26, Tables 3.5-3.6, Appendix I).

Discussion

Macroscale habitat evaluations can be used to distinguish spawning and nursery habitat for American shad within coastal plain systems. Since shad are thought to spawn over large areas, often encompassing several habitat types (Ross et al. 1993), microscale habitat assessments fail to describe spawning reaches over large areas. Examining habitat associations of shad eggs and larvae over a macroscale (m-km) can provide insight into habitat suitability issues for an entire system. By describing shad habitat over both micro and macroscales, reaches over large distances (km) were delineated as spawning or nursery habitat, and then characterized further with microscale parameters. Although there are obvious limitations in macroscale assessment of variables that change

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laterally and longitudinally, this approach allows for rapid assessment of systems for essential fish habitat when data are limiting. In this study, microscale parameters governed by hydrologic forces were extrapolated to encompass larger areas (m-km) based on tidal excursion estimates, and these allowed for application of local measurements over the entire river systems. Thus, in river systems where data are limited, a description of essential fish habitat may still be accomplished and then applied to management decisions.

Macroscale examination of the distribution of American shad eggs indicated that spawning on the Mattaponi and Pamunkey rivers predominately occurred within the upstream and mid-river segments. Spawning reaches were characterized by shallow depths (< 5 m), high DO (> 8 mg/L) and relatively high current velocity (0.3-1.0 m/s). Massmann (1952) also observed peak abundance of eggs along the middle segments of the Mattaponi and Pamunkey rivers with extensive flats (Lester Manor (96.2 - 98.1 km) to Gregory's Bar (109.2-111.0 km)) on the Pamunkey River and from Mattaponi (81.4-83.3 km) to Rickahock (92.5 - 94.4 km) on the Mattaponi River. Upstream and mid-river reaches may be optimal spawning habitat due to shallow water, high oxygen levels and high currents that may act to enhance mixing during spawning, prevent siltation or suffocation of eggs, and favor transport of hatchlings to salubrious feeding environments. Distributions of larvae extended into all three morphologic regions with the lowest densities in upper reaches, presumably due to downstream drift. Peaks in larval density occurred in mid-river reaches of both rivers, corresponding to the preponderance of upstream and mid-river spawning with subsequent downstream transport of larval stages. Additionally, tidal excursion distances are typically lowest in mid-river reaches, which

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may enhance larval retention (Figure 3.1). Spawning downstream may lead to larval transport out of favored nursery environments and enhance mortality. However, precise description of larval nursery habitats is difficult due to the lack of strong patterns evident in statistical comparisons. Logistic regression results consistently indicated that both principal component scores were significant for presence of eggs, but only one was typically significant for presence of larvae (Tables 3.5-3.6). This implies that stronger patterns existed for eggs than larvae and that spawning habitat may be more accurately described than nursery habitat. The less distinct pattern in distribution of larvae may be expected when the effects of downstream transport of larvae are considered.

Hydrographic Habitat Suitability

The ranges of the hydrographic parameters (DO, pH, secchi depth and temperature) observed with presence of eggs and larvae closely correspond to postulated HSI curves. One exception was that absences occurred in the upper optimal limit of temperature which is possibly due to limited samples. For both depth and current velocity, larvae displayed patterns different than eggs, thus a second HSI was developed and plotted separately for larvae. Downstream transport of larvae from spawning grounds likely produces the apparent differences in depth and current associations between eggs and larvae. While eggs were primarily collected in reaches of shallow depth, high DO and high current velocity, larvae were collected in reaches with variable depth and DO, and low current velocities (< 0.5 m/s). Research in other systems elucidated similar depth and current patterns. Shad spawning has been observed to take place in areas dominated by extensive shallow flats (Bigelow and Welsh 1925; Massmann 1952; Jenkins and Burkhead 1994). Ross et al. (1993) noted that the greatest spawning activity occurred at

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< 1 m depth, in low turbidity (<2 ntu) reaches of the Delaware River. Although some spawning was observed in all of the examined habitats, the highest activity was in the runs and the lowest in the pools and riffle pools, indicating some habitat selection by spawners.

Selection of spawning habitat was not accounted for with the hydrographic HSI models that rated all measured habitat as highly suitable (SI > 0.6) for shad spawning and nursery areas. Shad eggs were consistently absent from downstream habitats of the Mattaponi and Pamunkey rivers (68-80 km, 72-98 km, respectively), regardless of high habitat ratings. This implies habitat selection in these systems is not entirely based on the hydrographic parameters examined in this study. In addition to the physical habitat and shoreline/land use features that were considered, other parameters not incorporated into the models may be influencing the spawning reach selection of shad. These may include discharge and sizes of spawning runs.

Physical Habitat Suitability

HSI curves of the physical habitat were the least predictive. Reaches with low sinuosity values (1.2) contained similar densities of eggs and larvae as reaches with high values indicating that sinuosity in this system is not a good predictor of optimal shad spawning and nursery habitat. Likewise, overhang and sediment size were not the most effective descriptors of "good" habitat in a coastal plain estuary system. Coastal plain estuaries typically have low percentages of overhang and high percentages of sand/silt sediment, which is contrary to high gradient streams for which habitat evaluation indices are often developed. However, distribution patterns of egg and larvae may illustrate potential

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relationships among these variables. For both overhang and sediment size, eggs were distributed throughout the observed ranges, while larvae were collected in reaches with silt/mud only and less than 1% overhang values. These distribution patterns may occur due to the effects of passive downstream drift on egg and larval stages implying that overhang and sediment size are not of importance to pelagic, larval stages. The HSI curve for deadfall surface area corresponded to the distribution of shad eggs. Shad eggs were located in reaches with designated optimal habitat suitability with only one exception, while larvae were often collected in reaches with suboptimal habitat possibly due to downstream transport. This may be due to active selection by spawners or a function of the area itself. These upstream habitats are important to larval and juvenile stages for feeding (Massmann 1963; Crecco and Blake 1983), thus selection by spawners of reaches with extensive deadfall (where important larval and juvenile shad prey items originate) may be occurring to ensure retention within favorable upstream and mid-river nursery habitats. Peaks in density of eggs and larvae in high width:depth reaches, which represented broad mid-river bar reaches, substantiated the importance of these areas as spawning and nursery zones.

Physical habitat features were not the most accurate descriptors of optimal habitat for shad eggs and larvae. Utilizing the parameters deadfall surface area, overhang, sediment size, width:depth and sinuosity in the combined physical HSI model resulted in low habitat scores for river reaches which contained eggs. Although HSI scales were modified to allow for low-gradient features, high gradient features still resulted in high scores. Thus, only the upstream reaches (above km 105 on the Mattaponi River and km

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113 on the Pamunkey river) received scores approaching unity. The inclusion of width:depth ratios (≥ 40 is considered optimal habitat based on Rosgen (1996)), and the exclusion of overhang ratings allowed for a higher grading of downstream habitat, but it is difficult to ascribe ecological value to width:depth ratios. The ratio indicates whether a stream is relatively deep, but provides no information about depth diversity, which has been shown to influence stream fish communities (Wang et al. 1998). High width:depth ratios may simply be an accurate descriptor of coastal plain systems, and force higher habitat scores to result. Overhang was excluded from habitat ratings since it was a poor determinate of optimal shad spawning and nursery habitat within the examined coastal plain estuary system, which contained limited overhang percentages even in pristine conditions.

Shoreline/Land Use Habitat Suitability

The relationships of agricultural shoreline and land use to the presence of eggs and larvae differed. Shoreline was classified as grass throughout both agriculture and marsh areas, thus classified grass shoreline may indicate marsh reaches or agricultural shorelines. Land use more accurately depicts agriculture reaches and declines are noted in density of eggs and larvae, when greater than 40% of the reach is agriculture. Since overall residential land use was less than 5% in any given reach, no pattern could be elucidated with presence of eggs and larvae. Although shoreline residential percentages exceeded residential land use values, the impact of developed areas may be minimized in these rivers due to the lack of intense urbanization. Limburg and Schmidt (1990) observed increased variability in oxygen saturation levels near urban areas in the Hudson River and declines in abundance of eggs and larvae of anadromous fishes in reaches where

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urbanization was greater than 10%. The Hudson River contains much more intense urbanization than the Mattaponi and Pamunkey rivers, which may account for the differing results. Forested shoreline percentages more closely correspond to reported optimal habitat suitability than forested land use, but the patterns are similar. Shad eggs were primarily collected in reaches of > 60% forested and < 20% emergent marsh, which is indicative of upstream and mid-river reaches, while larvae were more dispersed.

Shoreline and land use were as accurate as microscale habitat measurements for prediction of American shad optimal spawning habitat. In the upstream and mid-river reaches, where spawning habitat was predominately located, habitat ratings were consistently high, and in downstream reaches ratings were more variable and eggs were absent. Highly forested reaches (> 60%) were good indicators of egg presence, while lower reach descriptors were indicative of egg absence. These results suggest there is strong potential to delineate potential American shad spawning and nursery habitat using macroscale parameters.

As noted by Bilkovic et al. (in review), annual indices of abundance of juvenile shad present a consistent pattern of higher abundance in the Mattaponi than Pamunkey River (mean recruitment (1991-1999): Mattaponi JAI, 1522.6; Pamunkey JAI, 247.0). While habitat features are a possible explanation to varying abundance, the parameters examined in this model either did not induce abundance differences between rivers, or suggested opposite patterns of recruitment. Hydrographic, physical habitat and shoreline/land use habitat ratings were all similar between the rivers. The physical

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habitat model (sinuosity, width:depth, overhand, deadfall and sediment size) rated more habitat unsuitable in the Mattaponi River than the Pamunkey River, a result in contrast to observed juvenile abundance. When overhang was removed from the model, the habitat ratings of the rivers were similar. Based on the hydrographic, physical and shoreline/land use parameters examined, there is no clear difference between the rivers that would account for varying production. Additional parameters to be considered include biotic controls, discharge and fishery impacts. Variance in these components between rivers could lead to differing juvenile abundance. Unfortunately, there is limited data at this time on predator and prey populations within these systems. Likewise, variation in fishing pressure between rivers cannot be determined due to the unknown impact by coastal fisheries on individual populations when the populations are mixed. The importance of hydrographic parameters, such as discharge, on juvenile abundance and larval transport were addressed in the following chapter (see Chapter 4).

A future effort may be the incorporation of variables influencing fish populations that are independent of habitat features into the HSI models. For example, Platts and Nelson (1988) noted the need for incorporation of natural fish population fluctuations into habitat-based models used to evaluate land use effects. It is imperative to keep in mind as populations of American shad fluctuate, spawning reaches will likely expand or shrink. If restoration efforts are successful the availability of suitable spawning areas may become limiting. If populations of shad increase, protection and restoration efforts

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should be expanded to match potential spawning and nursery habitat to ensure continued increases.

This study exemplifies basin-wide environmental assessments. Such an approach may be utilized in similar riverine systems to guide American shad restoration projects through identification of optimal habitats. It was a first attempt at developing an interchangeable watershed approach to fish habitat evaluation within East Coast river systems. While actual habitat evaluation techniques would vary amongst systems, the backbone of the protocol would be consistent. Using available data, this protocol allows for the rapid delineation of important habitats on a macroscale (m-km) combining both on-site and remotely sensing data. When possible, microscale parameter assessments may then be added to enhance the accuracy of the delineation, and to gather information of correlation between watershed and in-stream processes, which ultimately effect fish production.

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Table 3.1. Habitat Suitability Index (HSI) models for American shad egg and larval stages with primary literature sources for the given ranges. M = Mattaponi River; P = Pamunkey River; Cur = Current velocity; Temp = Water temperature; D = River depth.

Parameter	Optimal range (SI = 1)	Unsuitable range (SI = 0)	Primary Sources
Water temperature (°C)*	14.5-24.5	Temp <8; Temp >27	Ross et al. 1993; Stier and Crance 1985
Dissolved Oxygen (mg/L)*	>5.0	< 4.0	Stier and Crance 1985, Chittenden 1973
pH*	6.0-9.9	pH≤ 5.7; pH ≥10.0	Stier and Crance 1985; Bradford 1968; Leim 1924
Current velocity (m/s)	0.3-0.7	Cur =0; Cur >1.0	Ross et al 1993; Stier and Crance 1985
Salinity (ppt)	0-7.5	>7.5	Limburg and Ross 1995; Leim 1924
Secchi depth (m)*	≥0.3	0	Dadswell et al. 1983; Auld and Schubert 1978; Leim 1924
Freshwater discharge (m^3/s)	20.5-43.7 (M) 33.9-72.2 (P)	>100 (M) >150 (P)	Marcy 1976
River depth (m)	1.5-6.1	D ≤ 0.15; D ≥15.2	Ross et al 1993; Stier and Crance 1985; Walburg and Nichols 1967; Massmann 1952
Deadfall surface area (m^2)/1000m	>3.8	0	Fajen and Layzer 1993; Wallace and Benke 1984
Sediment size (3 Categories)	≥2	1	Williams and Bruger 1972; Walburg and Nichols 1967
Overhang cover (5 categories)	≥0.5	0	Karr and Schlosser 1978
Sinuosity	>1.3	1	Decamps 1993; Platts 1983; Zimmer and Bachmann 1978
Width:Depth	≥40	1	Rosgen 1996
Percent Forest/reach	≥80%	0%	Wang et al. 1997; Correll et al. 1992
Percent Urban/reach	≤10%	100%	Wang et al 1997; Limburg 1990
Percent Agriculture/reach	≤50%	100%	Wang et al. 1997; Lenat and Crawford 1994
Percent High Erosion/reach	>90%	< 7%	Wang et al. 1998

*Applicable to spawning adults, egg and larval stages

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Table 3.2. Habitat parameters examined for associations with the presence/absence of American shad eggs and larvae.

Parameter	Data Type	Measurement
Hydrographic		
Water temperature	continuous	YSI Meter: every meter
Station depth	continuous	Field measurements, topographic maps
Current velocity	continuous	Marsh-McBirney Current Meter: surface
Dissolved oxygen	continuous	YSI Meter: every meter
pH	continuous	pH meter: surface
Secchi depth	continuous	Secchi disk
Structural and morphological		
Deadfall surface area	continuous	Surface area of deadfall per 1000 m
Percentage of overhang	categorical	Visual estimate (0, 1-25, 26-50, 51-75, 76-100)
Sediment size	categorical	Visual estimate (gravel, sand, mud/silt)
Sinuosity	continuous	Channel length/straight line distance
Width: Depth	continuous	Average width: average depth per 1000m
Shoreline/Land use		
Forest	continuous	% per 1000 m
Agriculture	continuous	% per 1000 m
Urban	continuous	% per 1000 m
Percentage of high erosion	continuous	% per 1000 m

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Table 3.3. River features and land use for the upper, mid and lower regions of the Mattaponi and Pamunkey rivers.

	Mattaponi River			Pamunkey River		
Average per 1000m reach	Upper	Mid	Lower	Upper	Mid	Lower
Number of deadfall	37.4	7.1	2.8	30.4	13.4	6.3
Overhang (by category)	0.8	0.0	0.0	1.0	0.6	0.0
Number of Creeks	1.7	2.6	6.3	1.7	2.3	5.4
Width (m)	38.0	321.5	310.5	36.9	213.2	402.5
Channel Depth (m)	1.4	5.1	9.6	1.9	4.4	9.0
Sediment type (by category)	2.0	1.1	1.1	1.8	1.2	1.0
Sinuosity	1.4	1.2	1.5	1.3	1.6	1.8
Width: depth	28.6	76.5	34.2	24.6	50.1	53.8
Dissolved Oxygen (mg/L)	9.52	9.08	8.66	9.04	9.35	9.21
pH	6.88	7.09	6.88	7.26	7.23	7.31
Secchi Depth (m)	1.20	0.99	0.65	1.23	0.92	0.50
Current Speed (m/s)	0.51	0.31	0.46	0.37	0.35	0.26
Area (m^2) in 100m buffer						
Water	1,049,644	4,759,866	9,944,696	1,083,874	6,402,880	19,431,939
Developed	15,101	116,919	263,016	20,643	53,723	699,136
Crops and probable crops	549,452	599,924	1,334,975	1,542,838	1,477,078	1,401,276
Forest and woody wetlands	6,178,031	2,509,165	6,346,128	8,655,420	7,404,762	10,619,686
Emergent wetlands	342,260	1,958,389	9,338,577	911,078	1,824,218	11,464,159
Grass	262,336	504,669	575,992	1,319,940	670,983	650,063
Total area(m^2)	8,396,824	10,448,932	27,803,383	13,533,792	17,833,643	44,266,259
Total area (m^2) w/o Water	7,347,180	5,689,066	17,858,688	12,449,918	11,430,763	24,834,319
Land Use Percentages						
Water%	12.5	45.6	35.8	8.0	35.9	43.9
Developed%	0.2	1.1	0.9	0.2	0.3	1.6
Grass%	3.1	4.8	2.1	9.8	3.8	1.5
Crop %	6.5	5.7	4.8	11.4	8.3	3.2
Forest%	73.6	24.0	22.8	64.0	41.5	24.0
Emergent%	4.1	18.7	33.6	6.7	10.2	25.9

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Table 3.4. Median values and ranges of hydrographic, physical habitat, shoreline and land use data collected in the Mattaponi and Pamunkey rivers, 1997-1999. Corresponding figure labels for statistical analysis are in parentheses. Observed ranges = range of values in which eggs/and or larvae were observed. Sampled ranges = the entire range of values measured during the data collection. For each parameter a median of the sampled range is listed next to the parameter, and the median of the observed values for each of the life stages is listed next to the appropriate life stage.

	Mattaponi River			Pamunkey River		
		Range			Range	
Hydrographic features	Median	Observed	Sampled	Median	Observed	Sampled
Temperature (°C) (temp)	15.5			15.2		
Eggs	16.0	14.2-19.5	12.0-22.0	15.0	13.2-19.0	11.8-19.4
Yolk-sac larvae	15.9	12.4-19.6	12.0-22.0	15.6	12.3-16.9	11.8-19.4
Postlarvae	16.0	14.4-20.5	12.0-22.0	15.0	13.6-15.7	11.8-19.4
DO (mg/L) (do)	9.1			9.2		
Eggs	10.8	7.5-12.4	6.8-12.6	10.2	8.0-11.5	7.3-11.5
Yolk-sac larvae	8.2	7.5-11.3	6.8-12.6	9.6	8.8-10.6	7.3-11.5
Postlarvae	8.1	7.5-11.1	6.8-12.6	8.2	8.0-10.3	7.3-11.5
pH (ph)	6.9			7.2		
Eggs	6.9	6.5-7.9	5.9-9.3	7.2	6.5-8.5	6.5-8.5
Yolk-sac larvae	6.9	6.5-9.3	5.9-9.3	7.2	6.5-8.2	6.5-8.5
Postlarvae	6.9	6.5-9.3	5.9-9.3	7.2	6.8-8.5	6.5-8.5
Secchi depth (m) (secchi)	1.0			0.8		
Eggs	1.0	0.7-1.7	0.3-2.0	0.9	0.4-1.6	0.2-1.8
Yolk-sac larvae	1.0	0.5-1.5	0.3-2.0	0.6	0.3-1.1	0.2-1.8
Postlarvae	1.0	0.5-1.9	0.3-2.0	0.6	0.4-1.3	0.2-1.8
Depth (m) (depth)	3.3			3.7		
Eggs	2.1	0.9-5.0	0.9-10.0	3.5	1.0-5.0	0.9-12.0
Yolk-sac larvae	4.0	1.0-10.0	0.9-10.0	4.2	1.2-10.5	0.9-12.0
Postlarvae	4.0	1.0-8.0	0.9-10.0	5.0	2.0-11.0	0.9-12.0
Current speed (m/s) (current)	0.49			0.37		
Eggs	0.49	0.3-0.9	0-1.1	0.44	0-1.0	0-1.2
Yolk-sac larvae	0.48	0-0.6	0-1.1	0.18	0-0.4	0-1.2
Postlarvae	0.44	0-0.6	0-1.1	0.48	0.4-0.5	0-1.2
River Morphology						
Deadfall surface area (m^2/1000m)	6.6			16.0		
Eggs	14.1	2.8-70.7	0-82.9	16.0	0-33.9	0-56.5
Yolk-sac larvae	8.5	1.4-70.7	0-82.9	10.8	0-17.9	0-56.5
Postlarvae	5.4	1.4-70.7	0-82.9	12.2	0-27.3	0-56.5
Sinuosity (sinuose)	1.3			1.2		
Eggs	1.2	1-1.4	1.0-1.9	1.3	1.1-2.8	1.0-3.2
Yolk-sac larvae	1.2	1-1.7	1.0-1.9	1.7	1.2-3.2	1.0-3.2
Postlarvae	1.3	1.2-1.7	1.0-1.9	1.6	1.2-2.8	1.0-3.2
Width:depth (widthdepth)	33.1			30.6		
Eggs	39.3	18.4-152.0	12.0-224.4	32.4	7.9-97.9	7.9-284.1
Yolk-sac larvae	34.8	16.9-152.0	12.0-224.4	51.9	20.8-97.8	7.9-284.1
Postlarvae	37.0	16.9-152	12.0-224.4	39.1	7.9-97.8	7.9-284.1

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	Mattaponi River			Pamunkey River		
		Range			Range	
River Morphology	Median	Observed	Sampled	Median	Observed	Sampled
Sediment Size (sedave)	1			1		
Eggs	2	1-2	1-2.5	1	1-2	1-3
Yolk-sac larvae	1	1-2	1-2.5	1	1-2	1-3
Postlarvae	1	1-2	1-2.5	1	1-2	1-3
Overhang (over)	0			1		
Eggs	0.05	0-1	0-1	0.1	0-1	0-1
Yolk-sac larvae	0	0-1	0-1	0.1	0.05-1	0-1
Postlarvae	0	0-1	0-1	0.1	0.05-1	0-1
Width (m)	209.4			115.4		
Eggs	58.6	29.2-463.4	19.0-717.6	82.0	30.8-626.0	26.0-952.6
Yolk-sac larvae	216.4	35.8-463.4	19.0-717.6	293.9	60.2-626.0	26.0-952.6
Postlarvae	232.9	35.8-463.4	19.0-717.6	208.2	40.4-626.0	26.0-952.6
Creeks (creeks)	3			2		
Eggs	3	0-8	0-16	2	1-3	0-13
Yolk-sac larvae	3	0-8	0-16	3	2-10	0-13
Postlarvae	4	0-15	0-16	3	1-4	0-13
Channel average depth (m)	5.5			3.7		
Eggs	2.1	0.9-8.8	0.6-16.2	3.3	1.2-7.0	0.75-17.7
Yolk-sac larvae	4.6	2.0-12.8	0.6-16.2	5.9	2.9-12.2	0.75-17.7
Postlarvae	6.0	0.9-12.8	0.6-16.2	5.5	2.1-9.1	0.75-17.7

Shoreline (percentage)						
Forest (forestshl)	86.0			96.6		
Eggs	95.2	75.6-100	0-100	91.7	70.8-100	15.5-100
Yolk-sac larvae	76.1	42.6-100	0-100	95.8	74.2-100	15.5-100
Postlarvae	76.1	23.9-100	0-100	91.7	70.8-100	15.5-100
Residential (dev.res)	6.5			2.6		
Eggs	4.8	0-24.4	0-77	6.4	0-29.2	0-84.5
Yolk-sac larvae	18.7	0-38.5	0-77	4.2	0-25.7	0-84.5
Postlarvae	13.5	0-38.5	0-77	8.3	0-29.1	0-84.5
Grass (grassshl)	0			0		
Eggs	0	0	0-100	0	0-12.8	0-18.4
Yolk-sac larvae	0	0-57.3	0-100	0	0	0-18.4
Postlarvae	0	0-62.3	0-100	0	0-62.3	0-18.4
Marsh (marsh))	68.9			44.0		
Eggs	67.6	0-95.7	0-100	14.4	0-62.3	0-100
Yolk-sac larvae	67.6	0-100	0-100	43.5	0-100	0-100
Postlarvae	67.6	41.9-100	0-100	43.0	0-62.3	0-100
High Erosion (eroshigh)	0			0		
Eggs	0	0-15.9	0-50	0	0	0-34.6
Yolk-sac larvae	0	0-42.6	0-50	0	0	0-34.6
Postlarvae	0.07	0-42.6	0-50	0	0-1.6	0-34.6

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Land use (Percentage)	Mattaponi River Median	Mattaponi River Range Observed	Mattaponi River Range Sampled	Pamunkey River Median	Pamunkey River Range Observed	Pamunkey River Range Sampled
Forest (forestlu)	62.3			45.9		
Eggs	77.4	22.6-98.5	0-100	71.0	20.9-99.7	0-100
Yolk-sac larvae	68.4	0-91.1	0-100	63.9	0-99.7	0-100
Postlarvae	63.9	0-88.4	0-100	69.3	34.2-99.7	0-100
Residential (dev.reslu)	0			6.5		
Eggs	0.44	0-0.74	0-18.5	0	0-1.6	0-94.1
Yolk-sac larvae	0.49	0-0.74	0-18.5	0	0-1.6	0-94.1
Postlarvae	0.33	0-0.75	0-18.5	0.15	0-2.6	0-94.1
Crop (croplu)	6.19			0.17		
Eggs	5.8	0-32.3	0-75.0	10.5	0-79.1	0-90
Yolk-sac larvae	18.6	0-64.1	0-75.0	16.0	0-31.7	0-90
Postlarvae	12.5	0-64.1	0-75.0	9.2	0.009-57.2	0-90
Marsh (emergent)	17.0			12.8		
Eggs	11.1	0-54	0-100	6.9	0-37.8	0-100
Yolk-sac larvae	16.9	1.4-100	0-100	14.7	0-100	0-100
Postlarvae	21.0	1.4-100	0-100	8.2	0-37.8	0-100

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Table 3.5. Results of logistic regression of principal component scores 1 and 2 against presence of shad eggs for the Mattaponi and Pamunkey rivers. Coefficients (β) and standard deviations (s.d.) are shown. Odds ratios (Ψ) are given with lower and upper 95% confidence intervals. Log-likelihood values (LL) for each model and the G statistic for the log likelihood is given. Probability values (P-values) are shown for the G statistic.

EGG STAGE	**Principal Component 1 Scores**							
Parameter grouping	**β**	**s.d.**	**Ψ**	**lower**	**upper**	**LL**	**G**	**P-value**
Hydrographic	-0.299	0.135	0.74	0.57	0.97	-120.9	40.3	0.03*
Hydrographic with Current Velocity	0.469	0.135	1.60	1.23	2.08	-95.6	26.6	0.001**
Physical Habitat	0.460	0.405	2.51	1.13	5.55	-22.9	10.4	0.05*
Shoreline and Land use	0.736	0.310	2.09	1.14	3.83	-23.6	7.3	0.02*

	Principal Component 2 Scores							
	β	**s.d.**	**Ψ**	**lower**	**upper**	**LL**	**G**	**P-value**
Hydrographic	-0.995	0.182	0.37	0.26	0.53	-120.9	40.3	0.0001**
Hydrographic with Current Velocity	-0.536	0.161	0.59	0.43	0.80	-95.6	26.6	0.001**
Physical Habitat	0.919	0.405	2.51	1.13	5.55	-22.9	10.4	0.02*
Shoreline and Land use	0.088	0.478	1.09	0.43	2.79	-23.6	7.3	0.85

*, ** Significant at the 0.05 and 0.01 levels

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Table 3.6. Results of logistic regression of principal component scores 1 and 2 against presence of shad larvae for the Mattaponi and Pamunkey rivers. Coefficients (β) and standard deviations (s.d.) are shown. Odds ratios (Ψ) are given with lower and upper 95% confidence intervals. Log-likelihood values (LL) for each model and the G statistic for the log likelihood is given. Probability values (P-values) are shown for the G statistic.

LARVAL STAGES	**Principal Component 1 Scores**							
Parameter grouping	**β**	**s.d.**	**Ψ**	**lower**	**upper**	**LL**	**G**	**P-value**
Hydrographic	-0.100	0.100	0.91	0.75	1.10	-146.8	17.9	0.31
Hydrographic with Current Velocity	-0.341	0.145	0.71	0.54	0.95	-92.8	6.3	0.02*
Physical Habitat	-0.678	0.251	0.51	0.31	0.83	-21.6	9.5	0.007**
Shoreline and Land use	-1.690	0.654	0.19	0.05	0.67	-18.4	13.7	0.01*

	Principal Component 2 Scores							
	β	**s.d.**	**Ψ**	**lower**	**upper**	**LL**	**G**	**P-value**
Hydrographic	0.586	0.149	1.80	1.34	2.40	-146.8	17.9	0.0001**
Hydrographic with Current Velocity	0.127	0.162	1.14	0.83	1.56	-92.8	6.3	0.43
Physical Habitat	-0.137	0.394	0.87	0.40	1.89	-21.6	9.5	0.73
Shoreline and Land use	1.128	0.936	3.09	0.49	19.36	-18.4	13.7	0.23

*, ** Significant at the 0.05 and 0.01 levels

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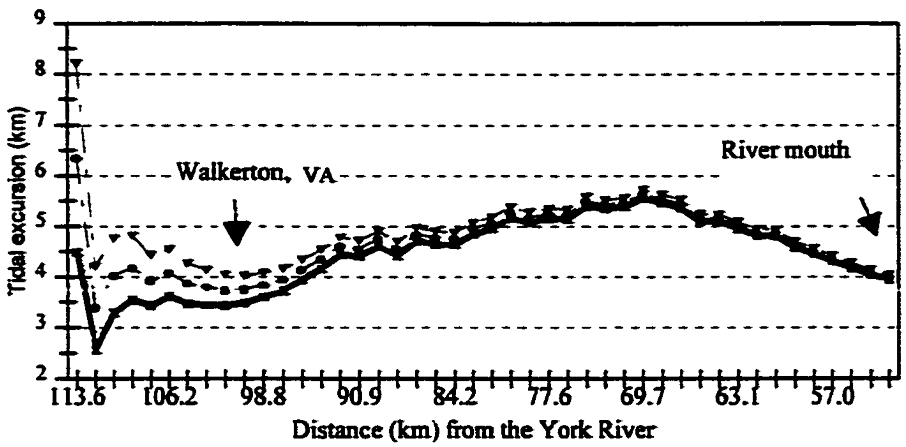
a)



b)

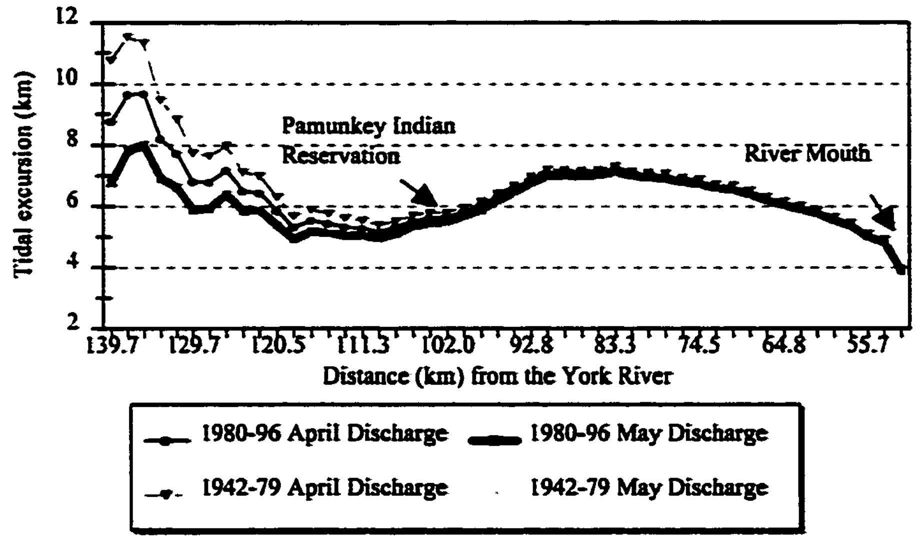


Figure 3.1. Tidal excursion estimated from cross-sectional area, maximum tidal current, and median discharge for the a) Mattaponi and b) Pamunkey rivers. Discharge is a median monthly value based on data from 1942-1979 and 1980-1996. Discharge measurements were obtained from USGS at Beulahville, Mattaponi River and Hanover, Pamunkey River.

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Figure 3.2. Shoreline attributes and land use features in the Mattaponi River.

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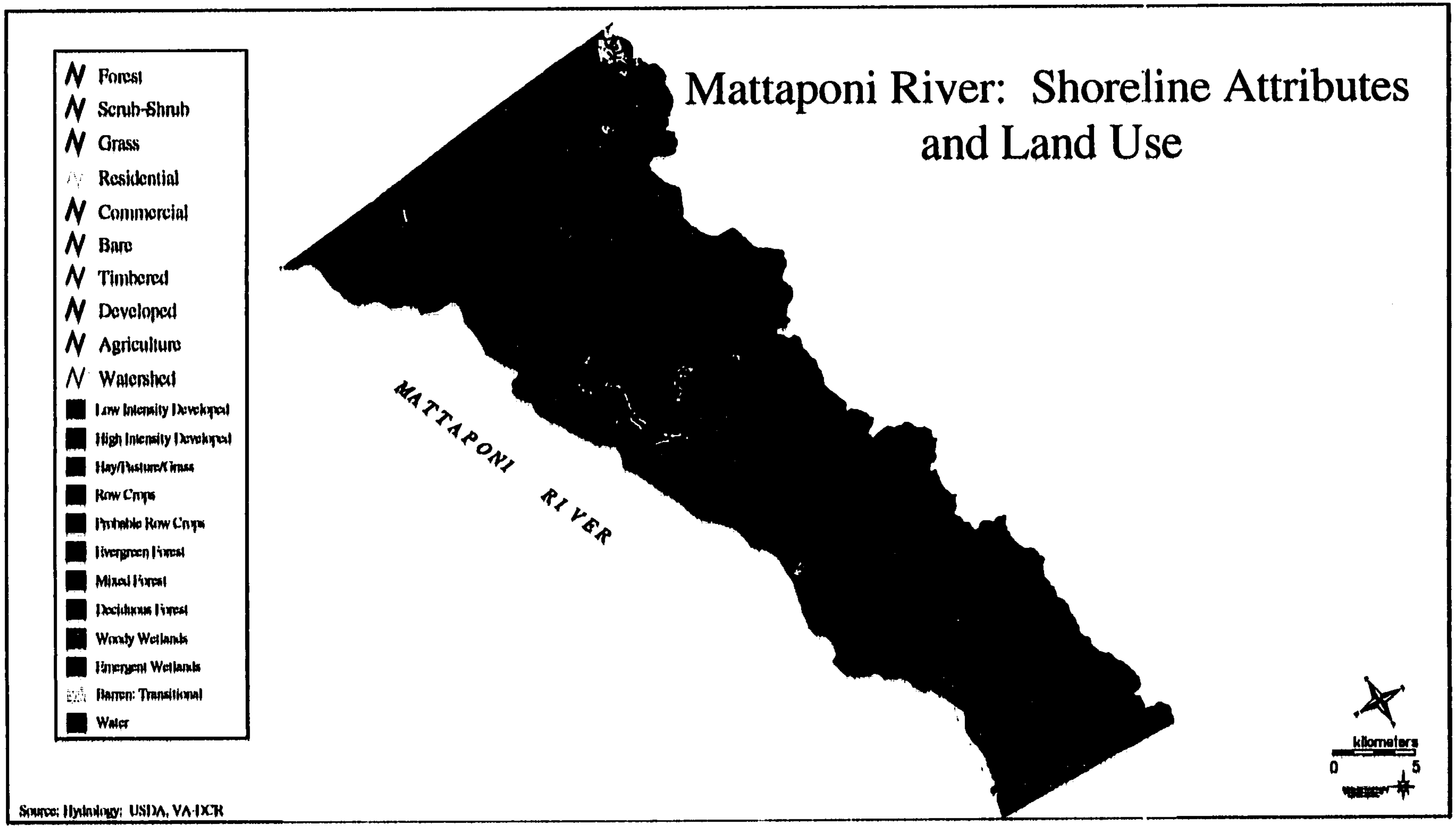

Figure 3.3. Shoreline attributes and land use features in the Pamunkey River.

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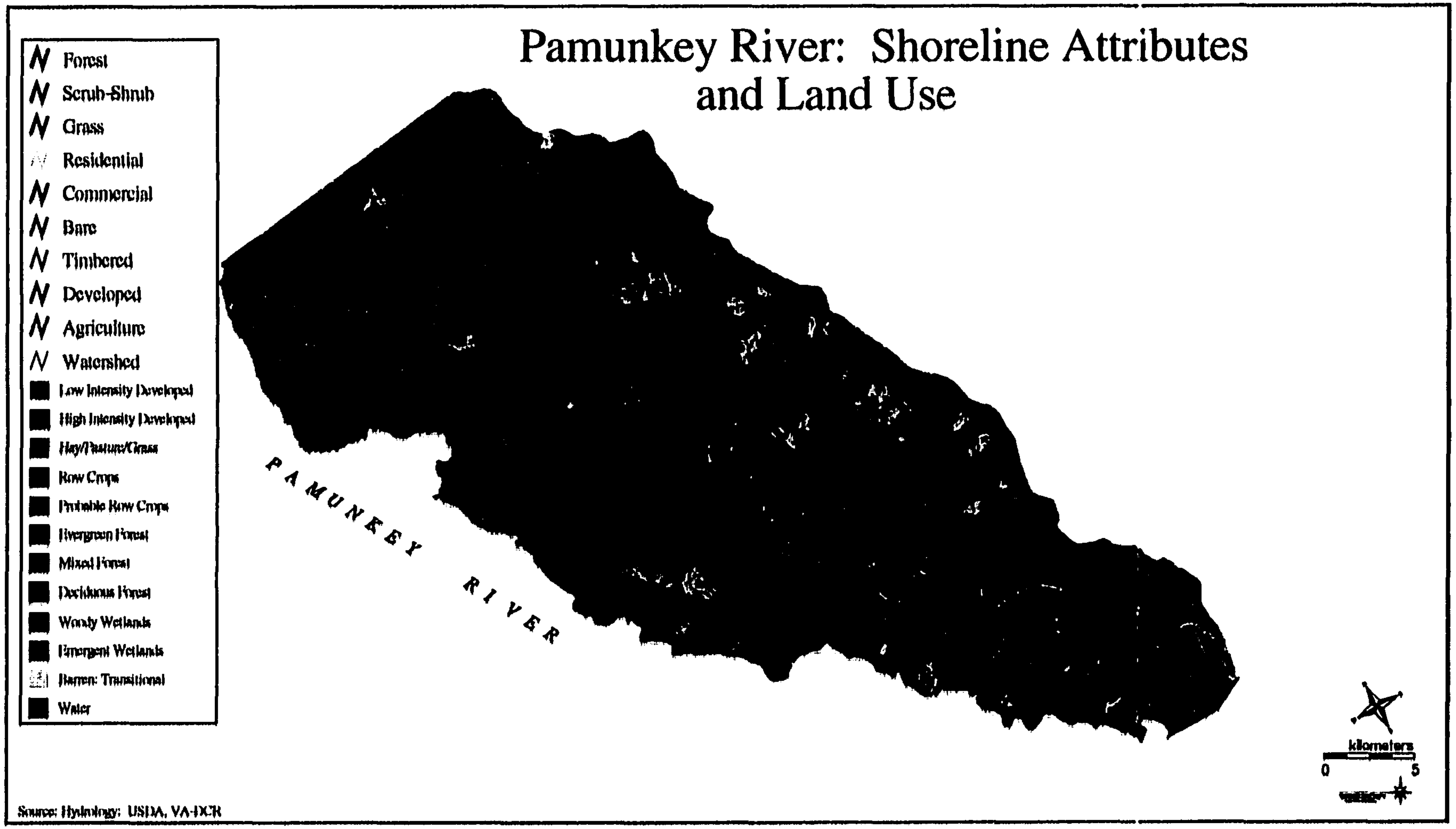

Figure 3.4. Spawning locations of American shad in the Mattaponi and Pamunkey rivers with delineation of upstream, mid-river and downstream segments superimposed.

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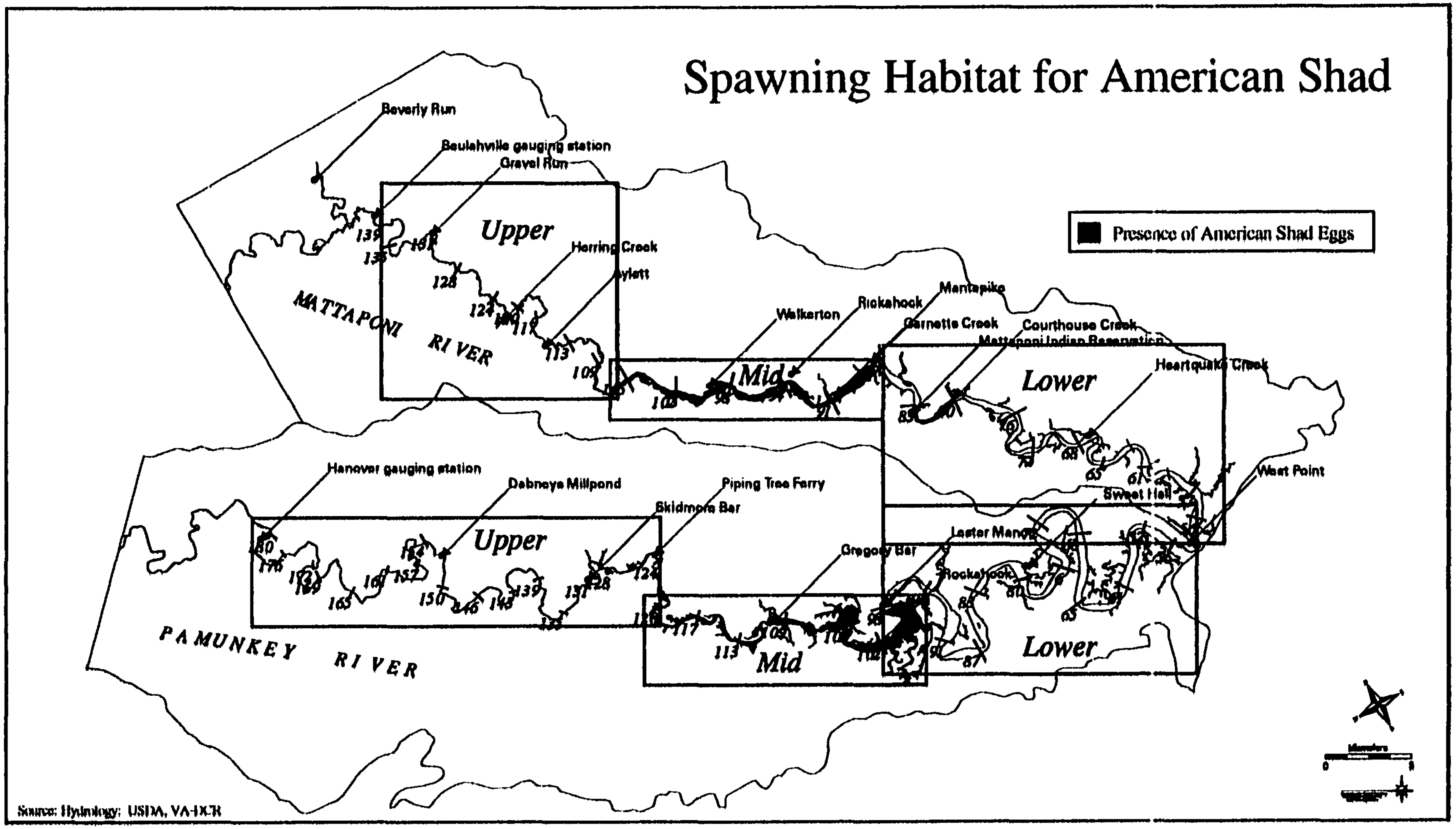

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Figure 3.5. Larval nursery locations of American shad in the Mattaponi and Pamunkey rivers with delineation of upstream, mid-river and downstream segments superimposed.

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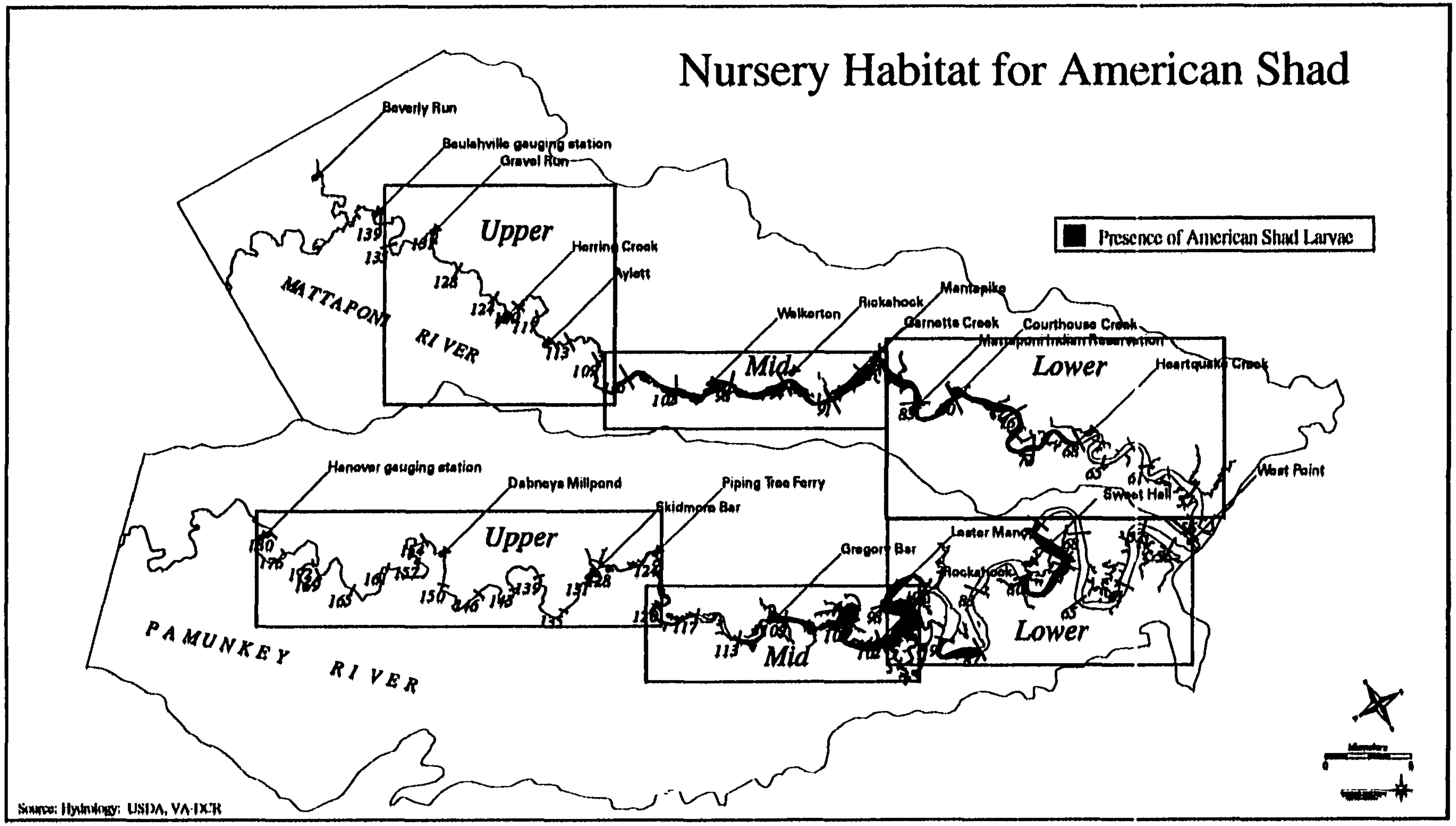

Figure 3.6. Distribution of American shad eggs and larvae in relation to hydrographic on the Mattaponi and Pamunkey rivers, 1997-1999. Habitat Suitability Index (HSI) models and corresponding regression equations for water temperature, depth, current velocity, DO, pH, and secchi depth are superimposed on data from this study for comparison.

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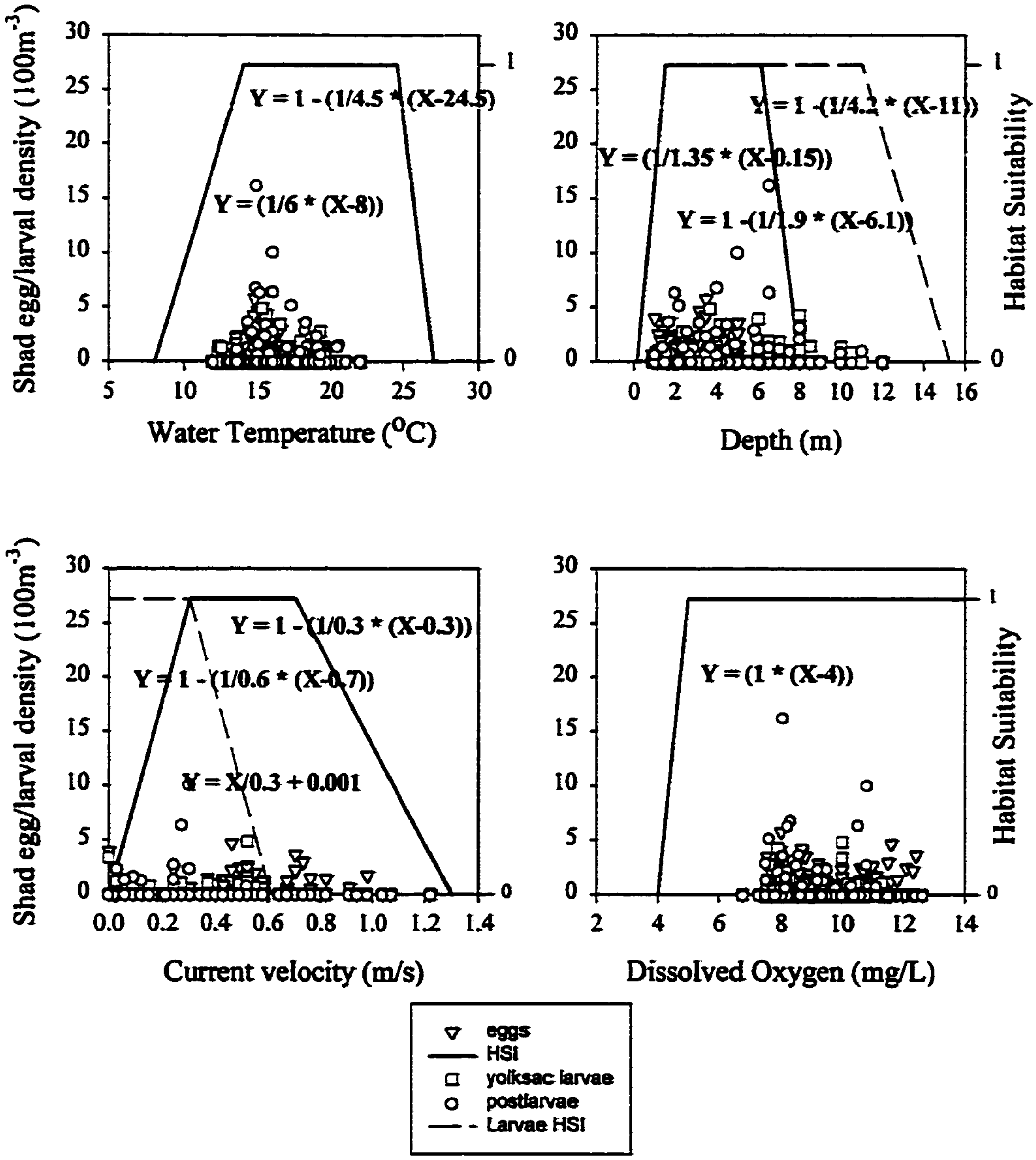

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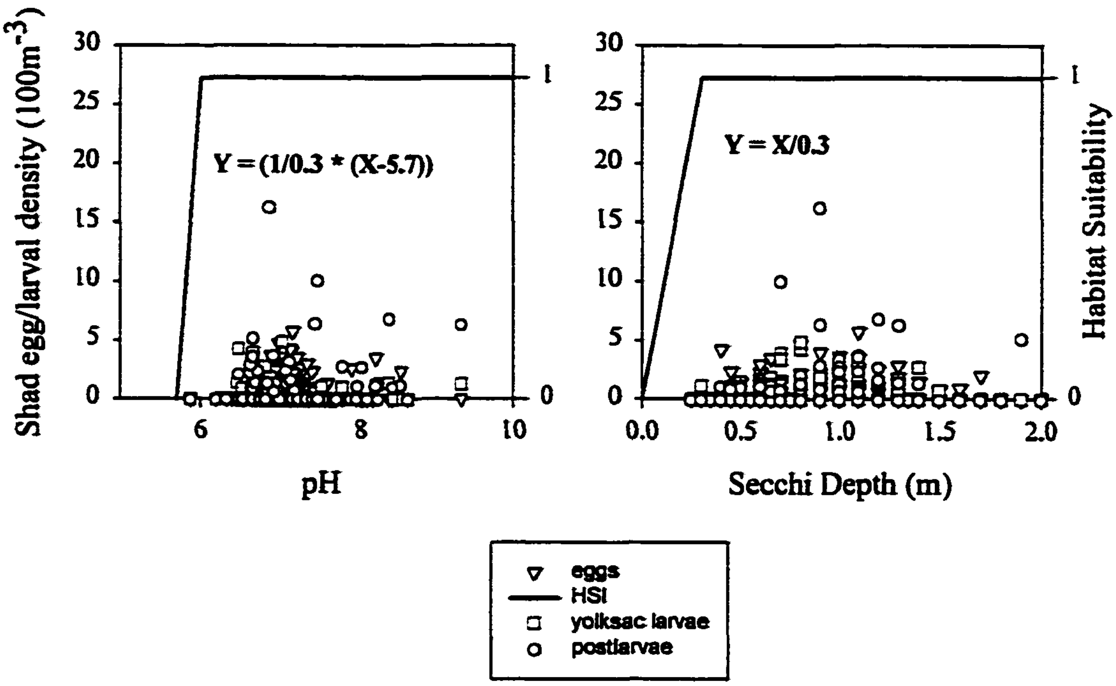

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Figure 3.7. Distribution of American shad eggs and larvae in relation to physical habitat features on the Mattaponi and Pamunkey rivers, 1997-1999. Habitat Suitability Index (HSI) models and corresponding regression equations for deadfall/area, overhang, sediment size, sinuosity, and width:depth are superimposed on data from this study for comparison.

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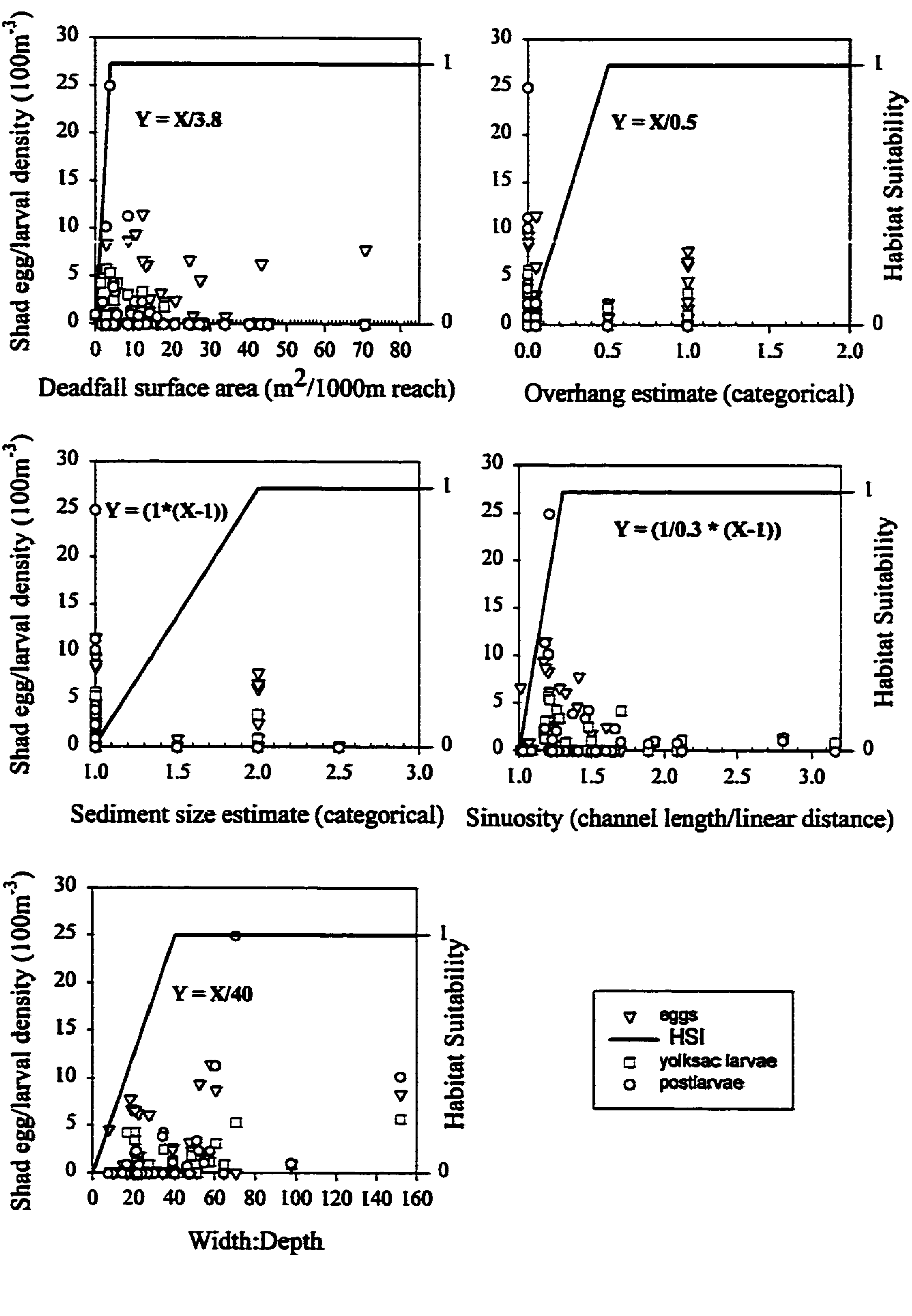

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Figure 3.8. Distribution of American shad eggs and larvae in relation to shoreline and land use features on the Mattaponi and Pamunkey rivers, 1997-1999. Habitat Suitability Index (HSI) models and corresponding regression equations for percent residential (urban), forested, marsh, agriculture, and high erosion are superimposed on data from this study for comparison.

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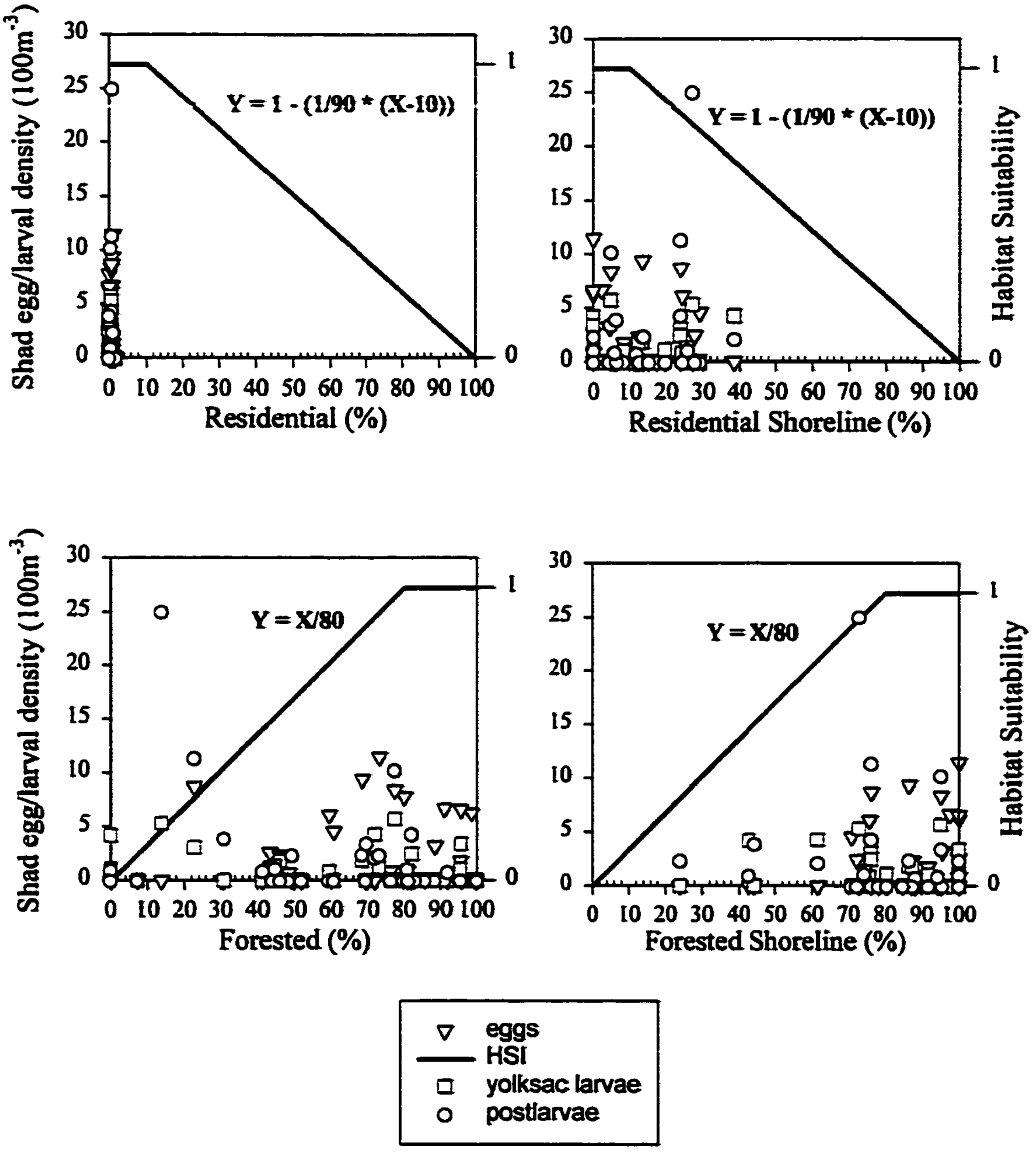

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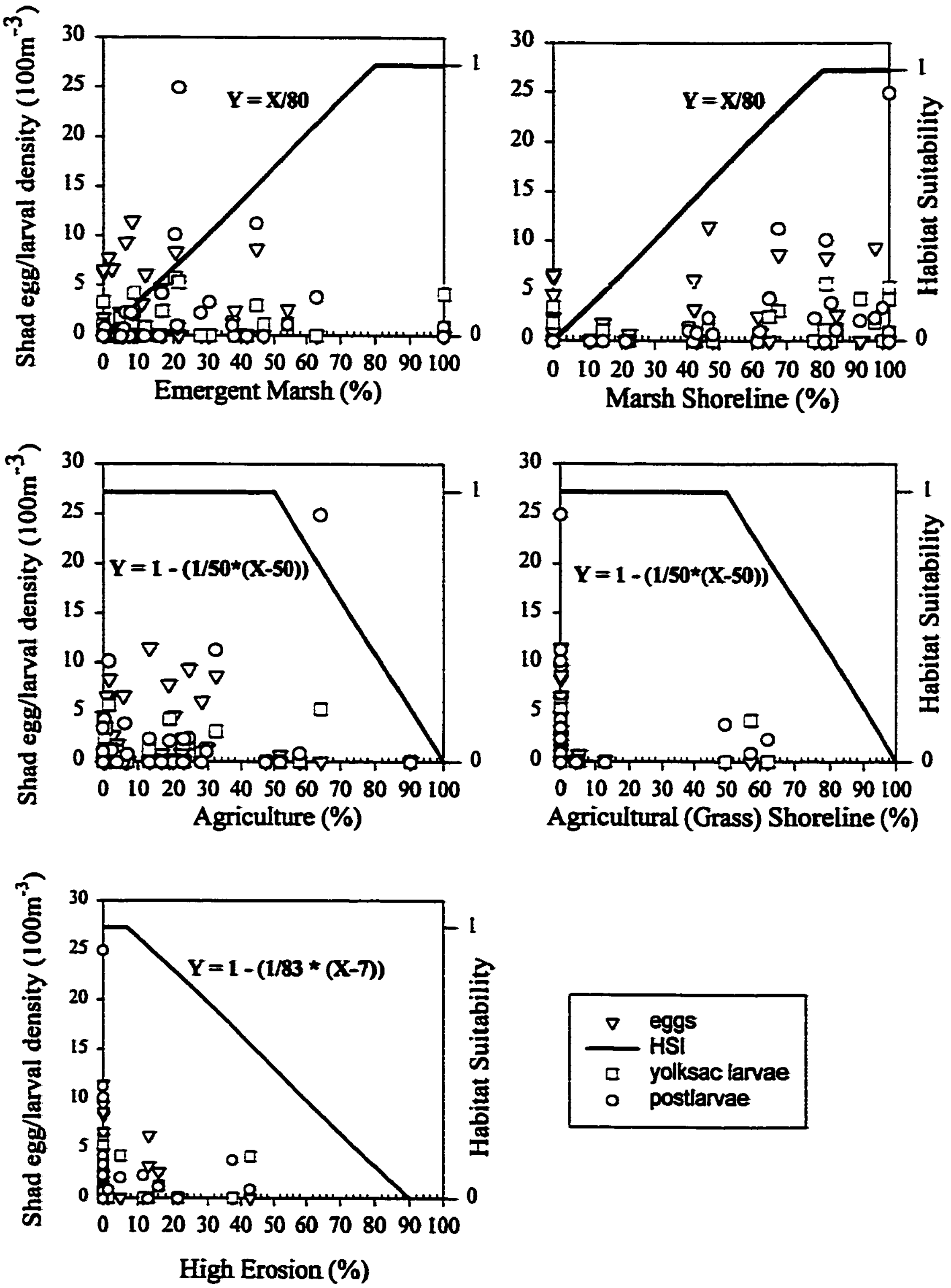

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Figure 3.9. Habitat suitability ratings based on the hydrographic parameters water temperature, depth, DO, pH, salinity, current velocity, and secchi depth for American shad eggs in the Mattaponi River. Hydrographic data was obtained during 1997-1999 ichthyoplankton collections.

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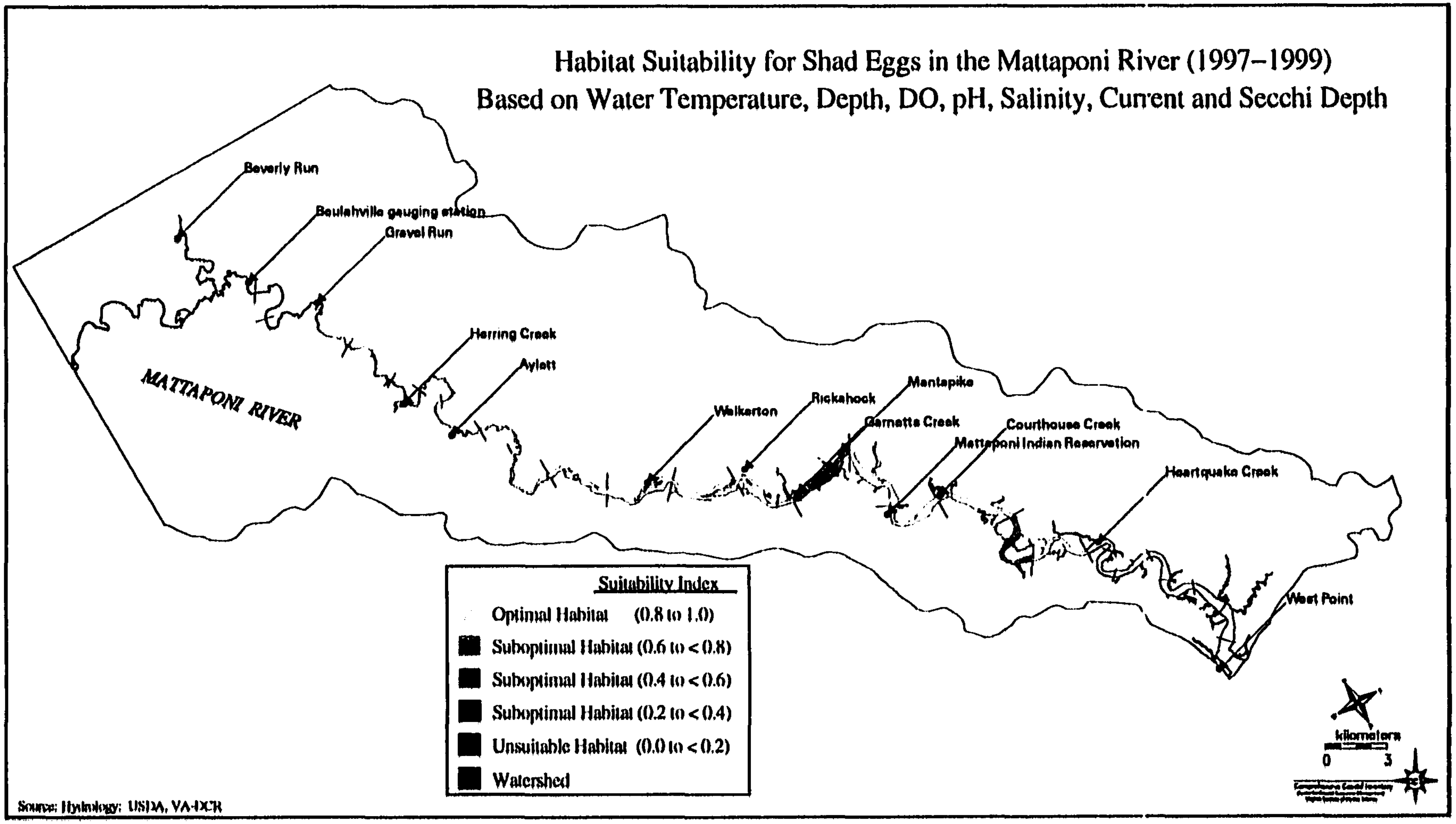

Figure 3.10. Habitat suitability ratings based on the hydrographic parameters water temperature, depth, DO, pH, salinity, current velocity, and secchi depth for American shad eggs in the Pamunkey River. Hydrographic data was obtained during 1997-1999 ichthyoplankton collections.

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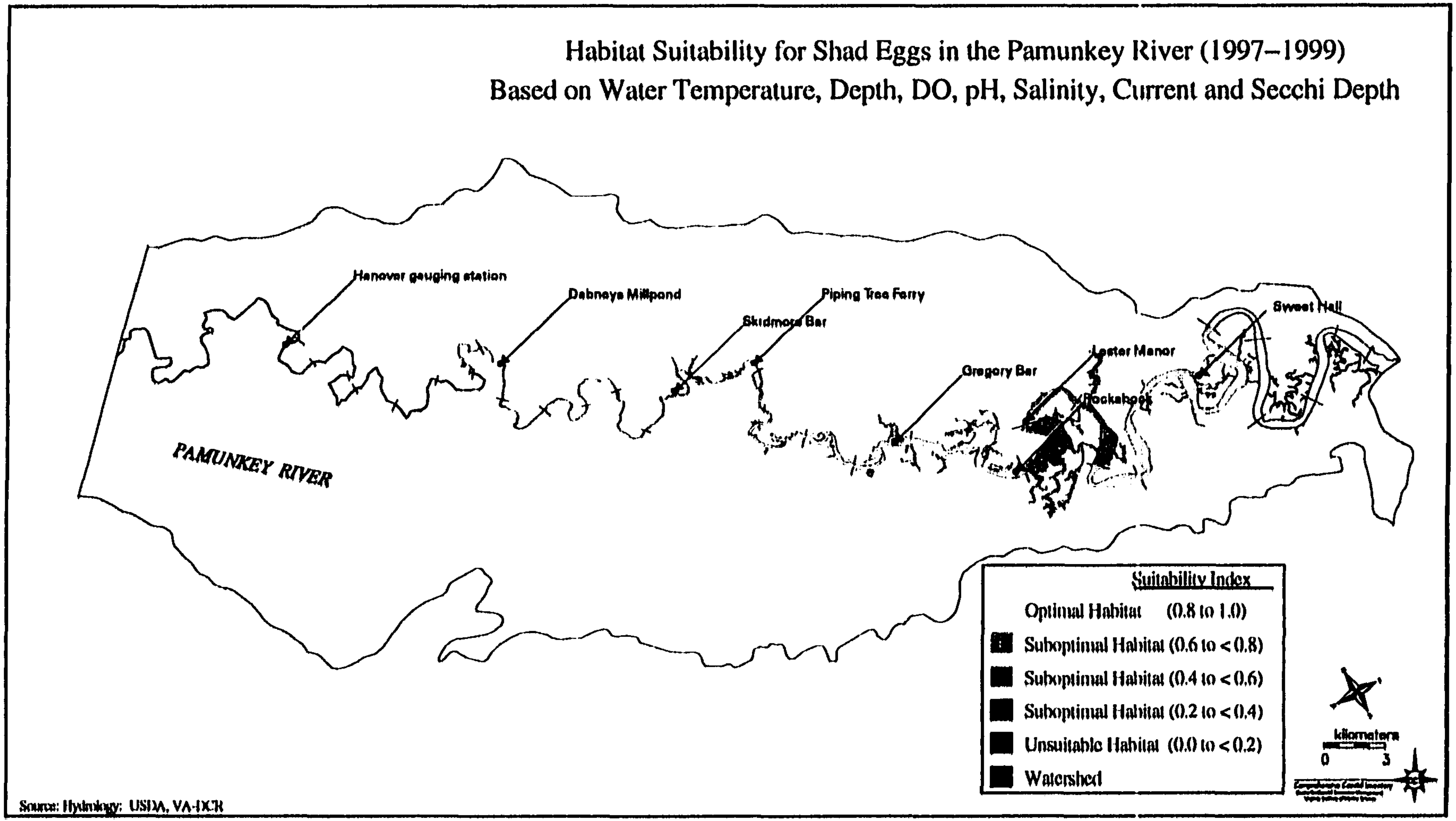

Figure 3.11. Habitat suitability ratings based on the hydrographic parameters water temperature, depth, DO, pH, salinity, current velocity, and secchi depth for American shad larvae in the Mattaponi River. Hydrographic data was obtained during 1997-1999 ichthyoplankton collections.

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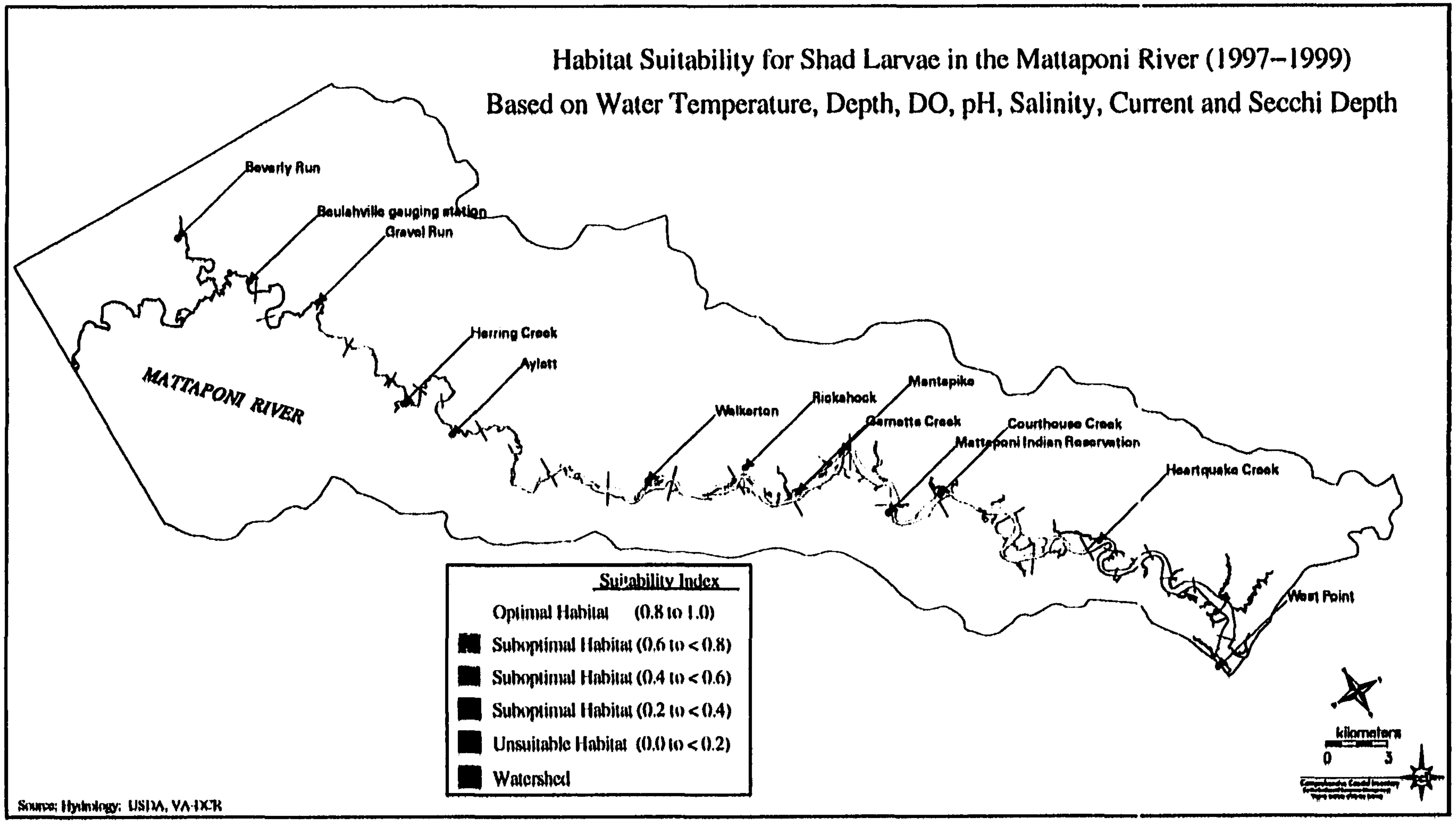

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Figure 3.12. Habitat suitability ratings based on the hydrographic parameters water temperature, depth, DO, pH, salinity, current velocity, and secchi depth for American shad larvae in the Pamunkey River. Hydrographic data was obtained during 1997-1999 ichthyoplankton collections.

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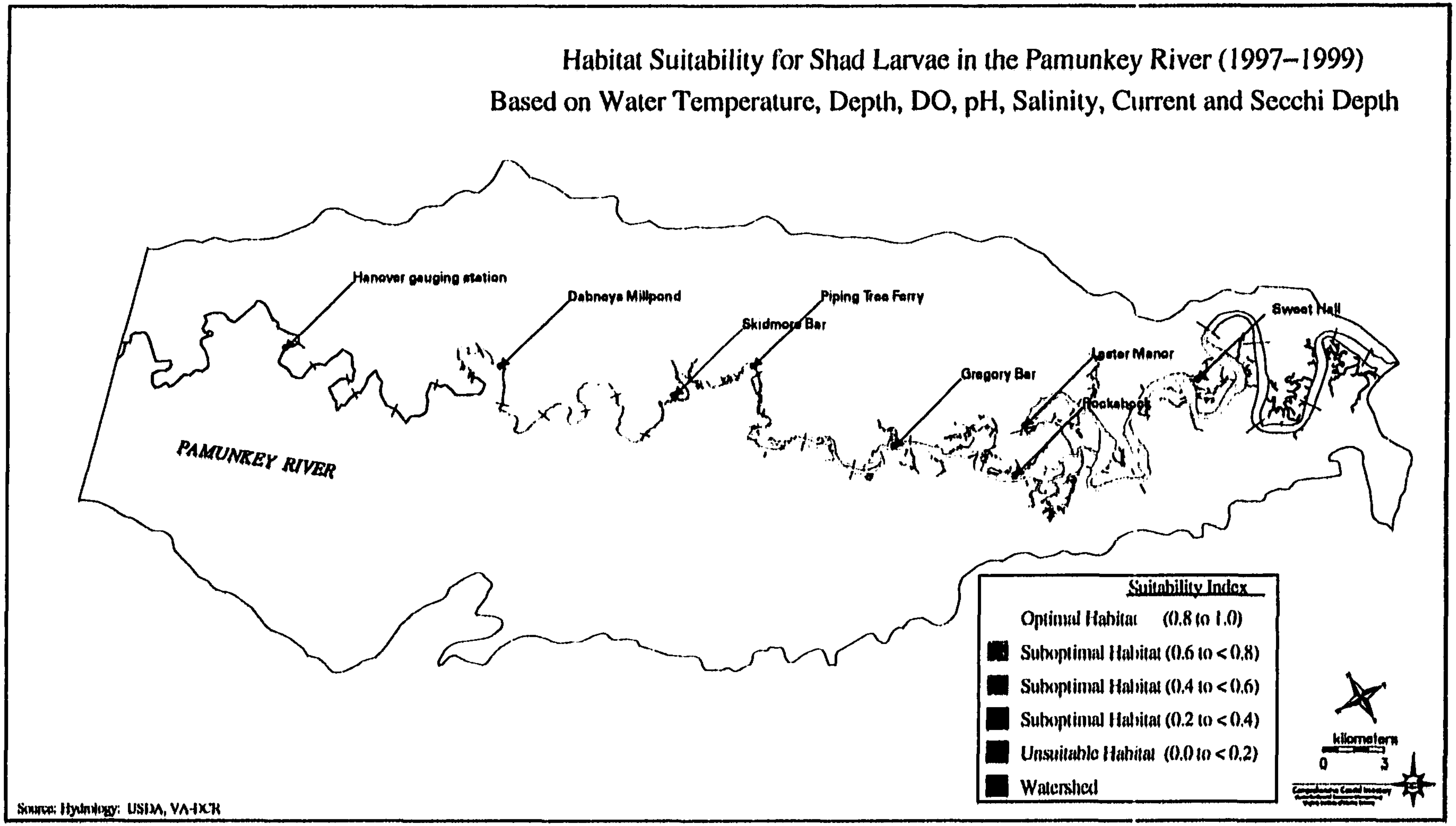

Figure 3.13. Habitat suitability ratings based on the physical habitat parameters sinuosity, width:depth, overhang, deadfall and sediment size for American shad eggs and larvae in the Mattaponi River.

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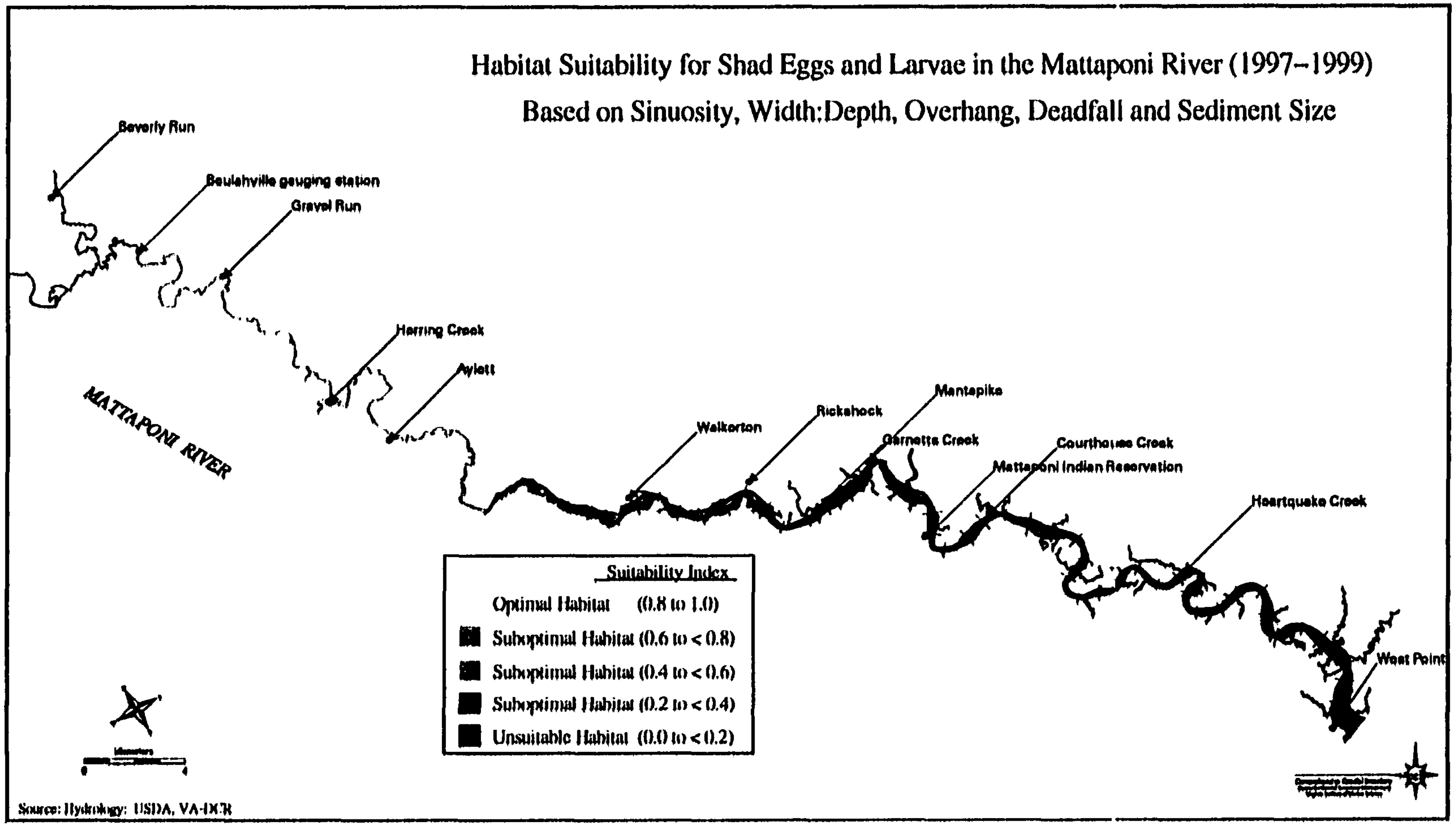

Figure 3.14. Habitat suitability ratings based on the physical habitat parameters sinuosity, width:depth, overhang, deadfall and sediment size for American shad eggs and larvae in the Pamunkey River.

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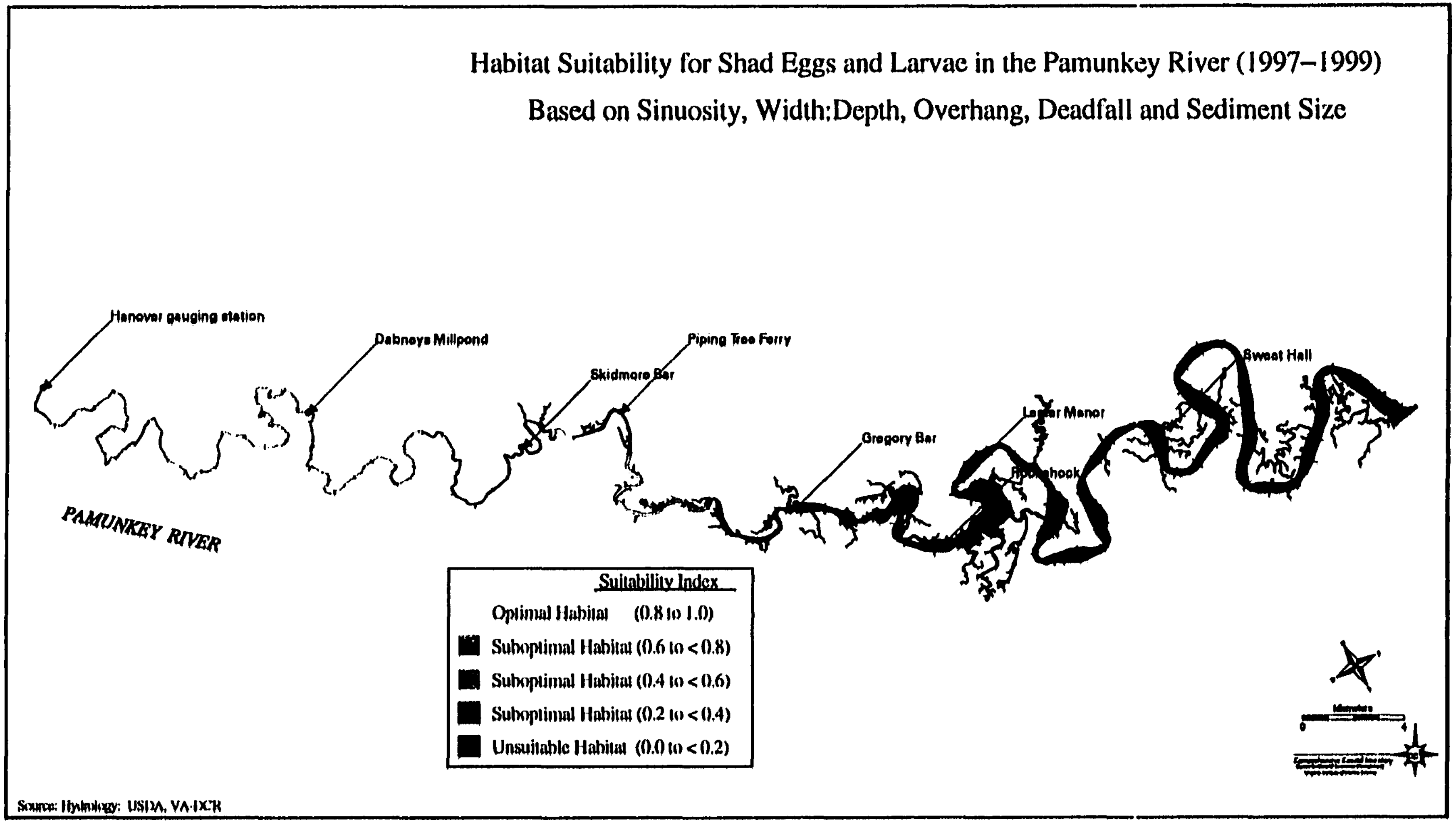

Figure 3.15. Habitat suitability ratings based on the physical habitat parameters sinuosity, width:depth, deadfall and sediment size (excluding overhang) for American shad eggs and larvae in the Mattaponi River.

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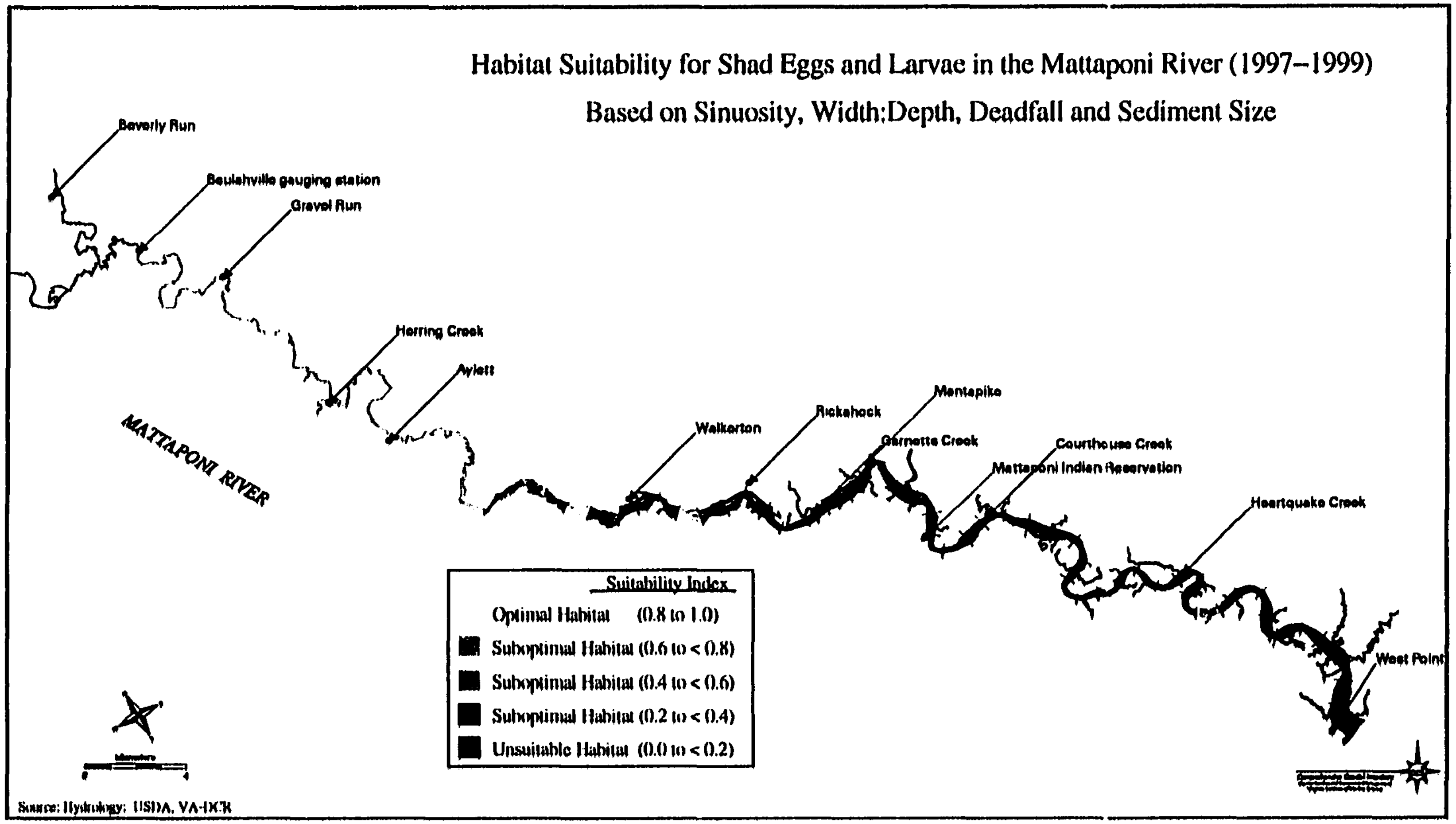

Figure 3.16. Habitat suitability ratings based on the physical habitat parameters sinuosity, width:depth, deadfall and sediment size (excluding overhang) for American shad eggs and larvae in the Pamunkey River.

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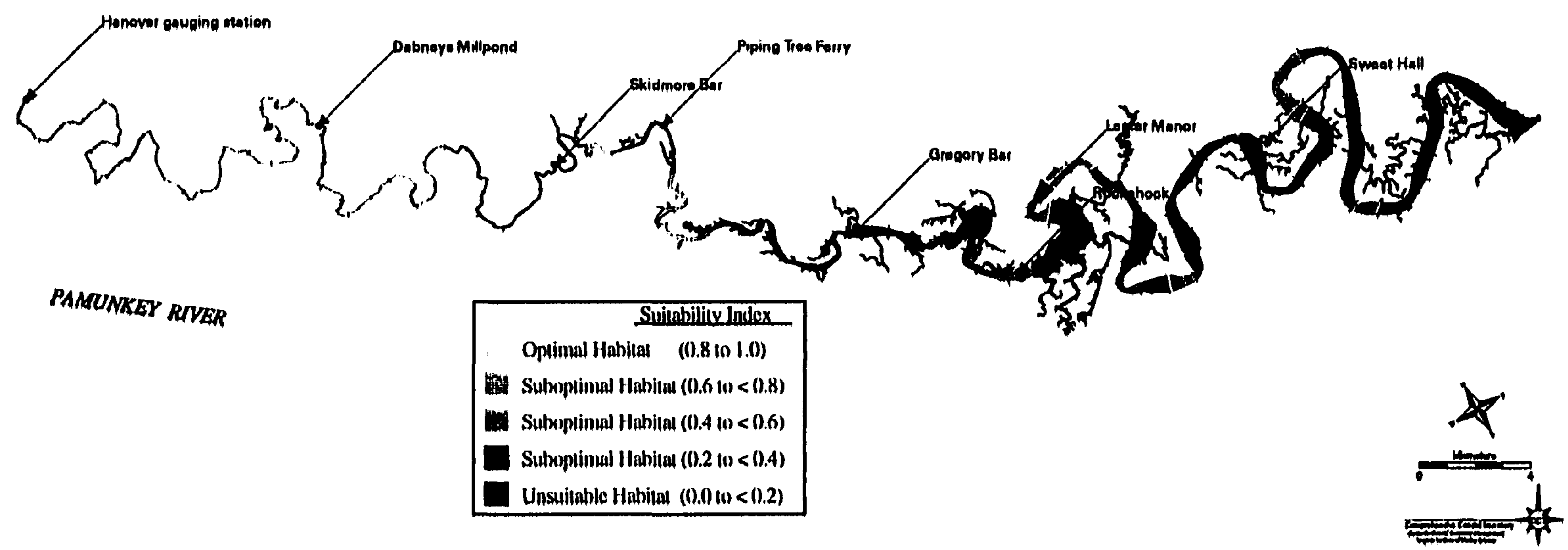
Habitat Suitability for Shad Eggs and Larvae in the Pamunkey River (1997–1999)
Based on Sinuosity, Width:Depth, Deadfall and Sediment Size



Source: Hydrology; USDA, VA-DCR

Figure 3.17. Habitat suitability ratings based on the shoreline features agriculture, forest, developed and high erosion for American shad eggs and larvae in the Mattaponi River.

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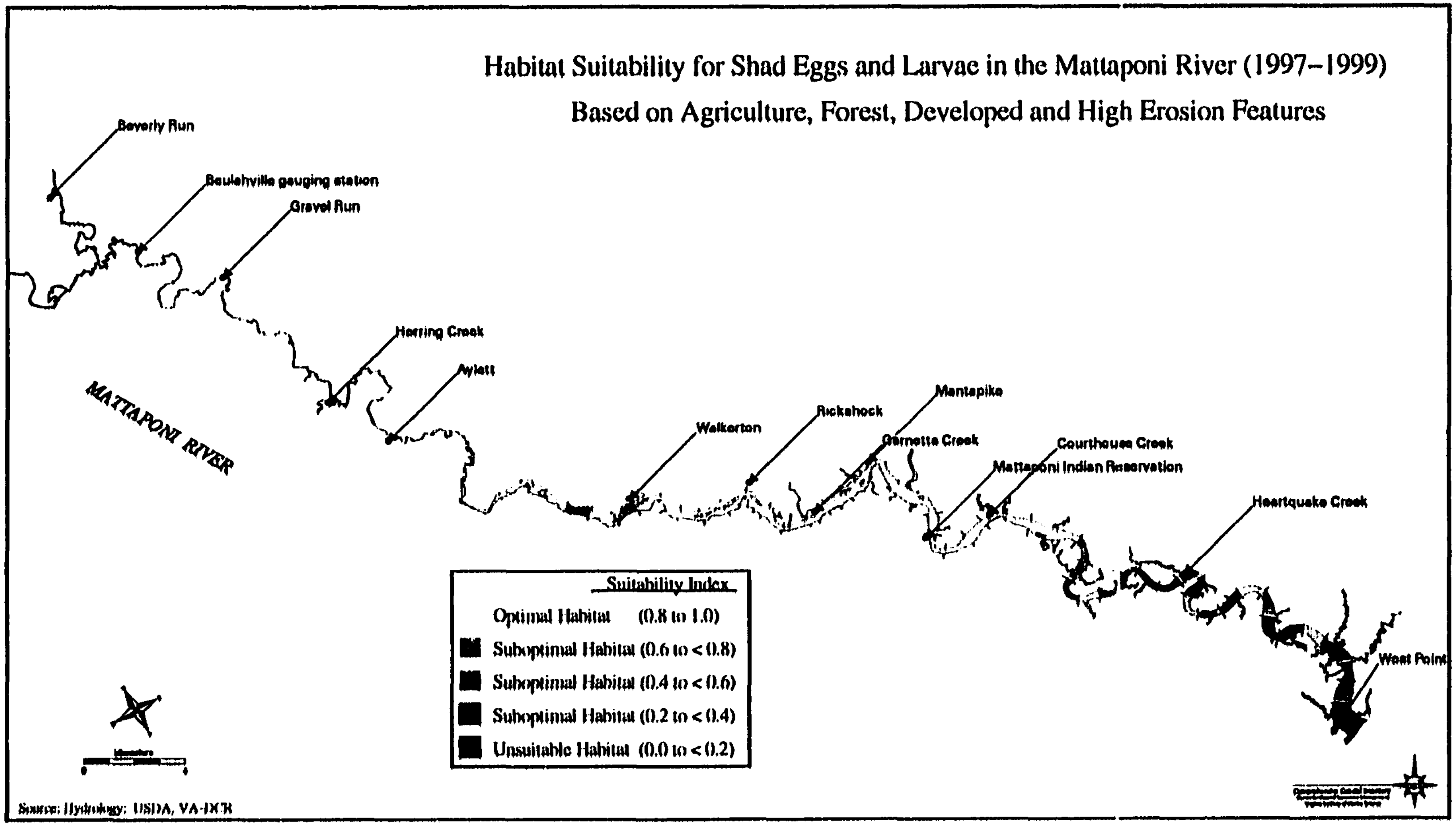

Habitat Suitability for Shad Eggs and Larvae in the Mattaponi River (1997–1999)
Based on Agriculture, Forest, Developed and High Erosion Features

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Figure 3.18. Habitat suitability ratings based on the shoreline features agriculture, forest, developed and high erosion for American shad eggs and larvae in the Pamunkey River.

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Habitat Suitability for Shad Eggs and Larvae in the Pamunkey River (1997–1999)
Based on Agriculture, Forest, Developed and High Erosion Features

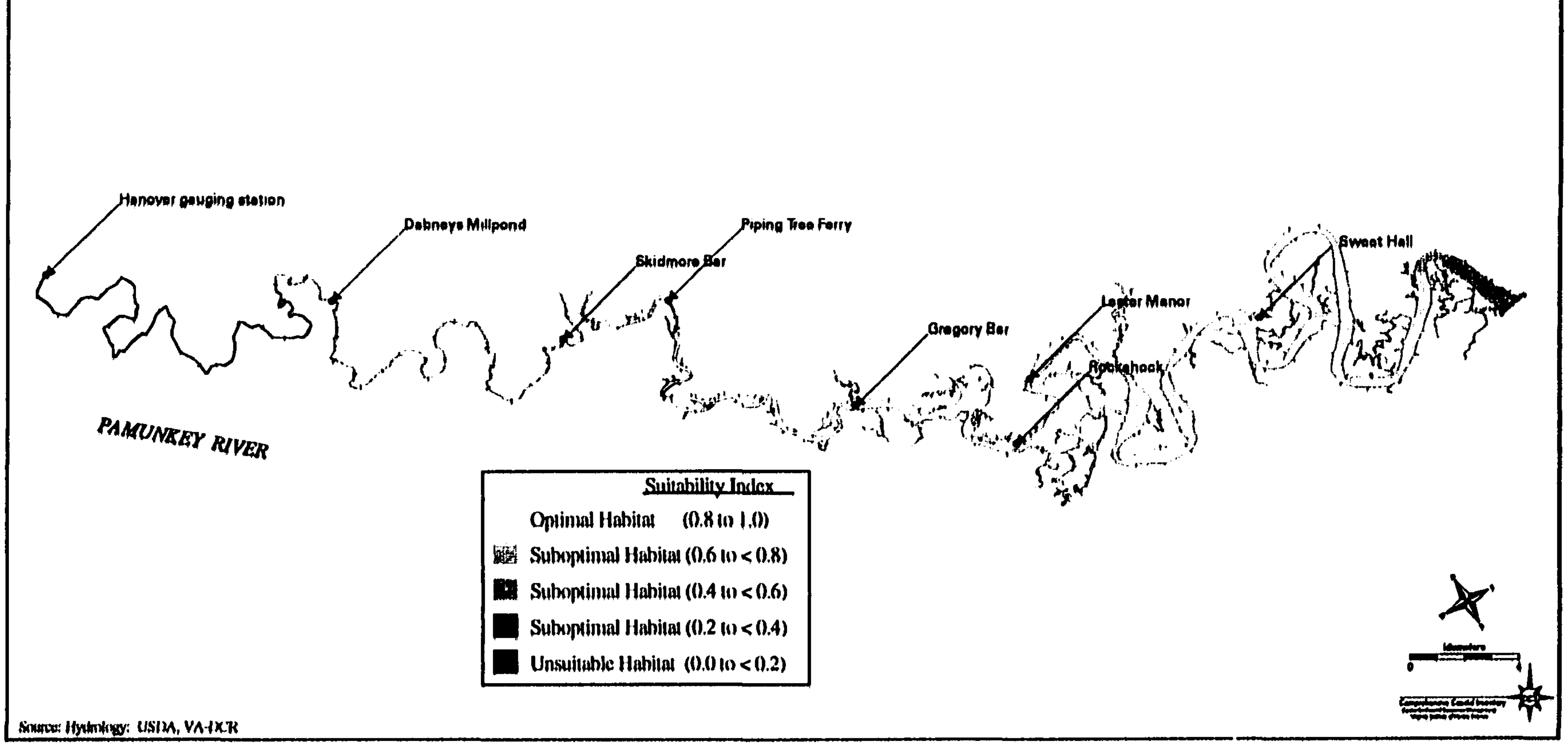

Figure 3.19. Habitat suitability ratings based on the adjacent land use features agriculture, forest and developed for American shad eggs and larvae in the Mattaponi River.

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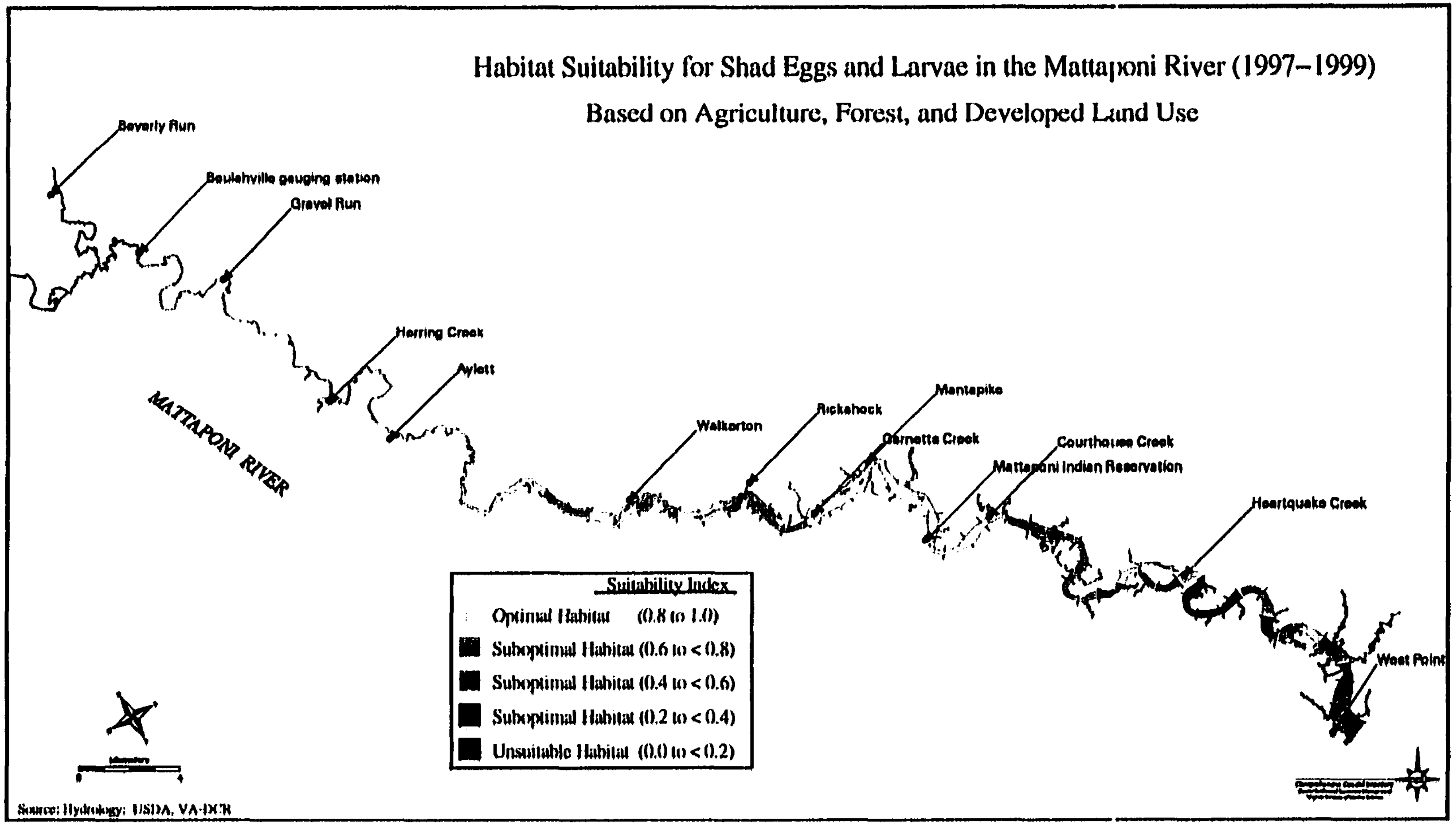

Figure 3.20. Habitat suitability ratings based on the adjacent land use features agriculture, forest and developed for American shad eggs and larvae in the Pamunkey River.

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Habitat Suitability for Shad Eggs and larvae in the Pamunkey River (1997–1999)
Based on Agriculture, Forest, and Developed Land Use

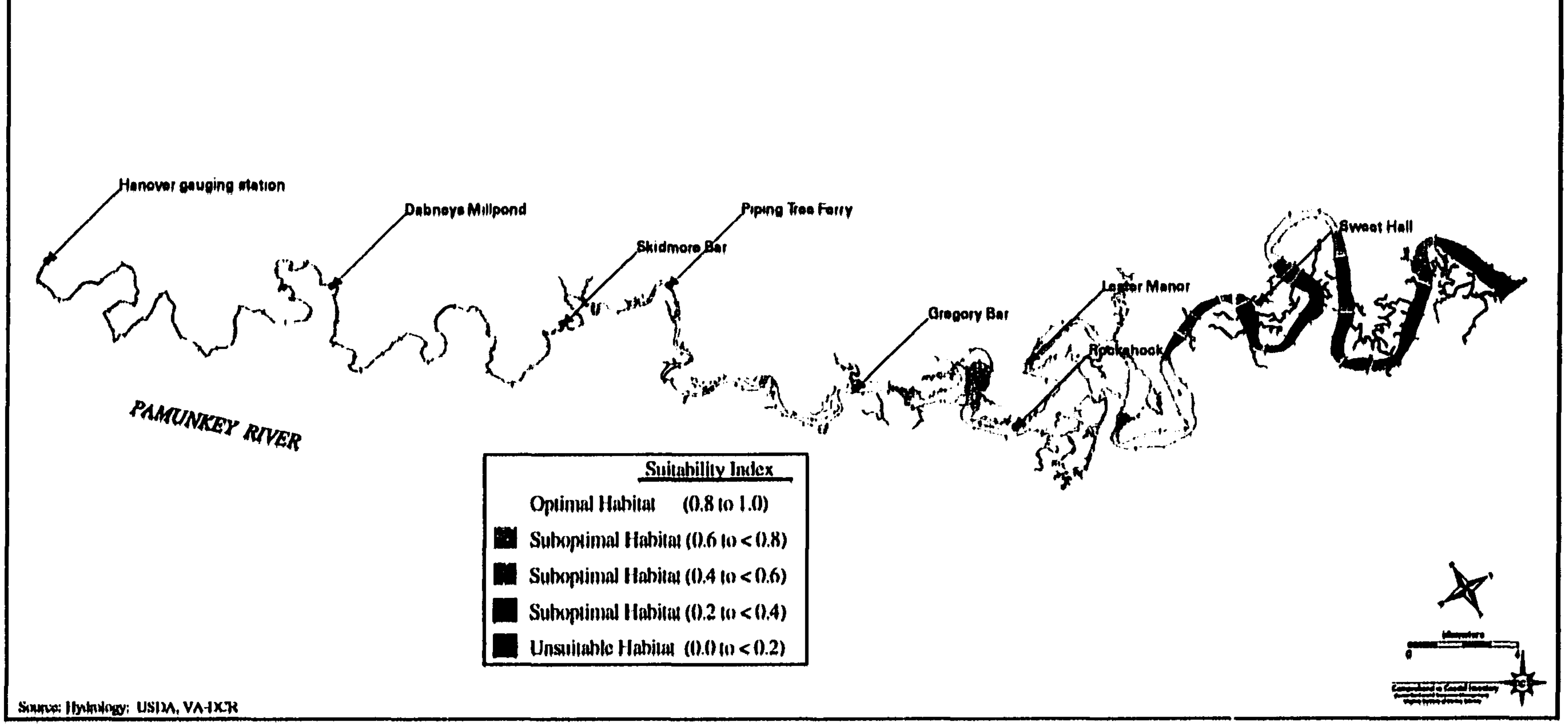

Figure 3.21. Cumulative habitat suitability ratings based on the land use features agriculture, forest and developed for American shad eggs and larvae in the Mattaponi River.

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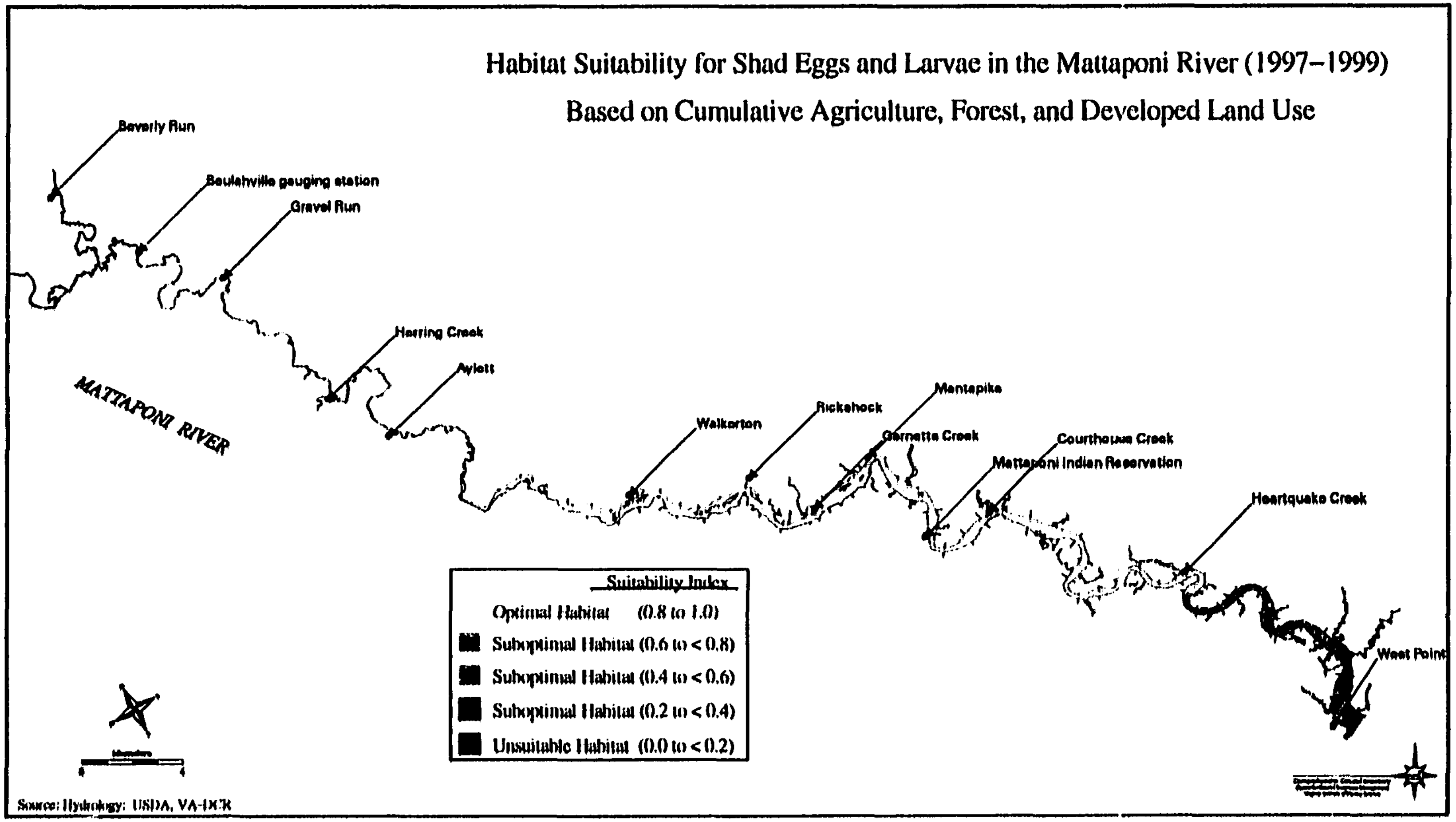

Figure 3.22. Cumulative habitat suitability ratings based on the land use features agriculture, forest and developed for American shad eggs and larvae in the Pamunkey River.

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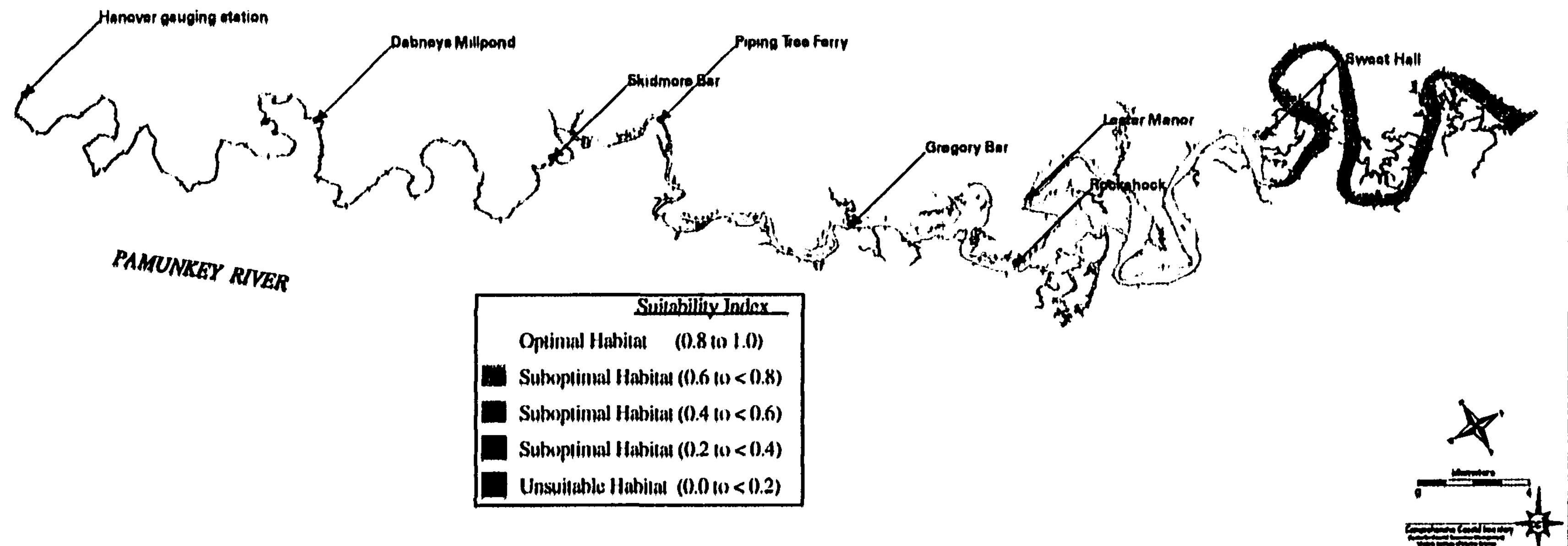
Habitat Suitability for Shad Eggs and larvae in the Pamunkey River (1997–1999)

Based on Cumulative Agriculture, Forest, and Developed Land Use



Source: Hydrology: USDA, VA-DCR

Figure 3.23. Combined habitat ratings of physical habitat, shoreline and land use features for American shad eggs and larvae in the Mattaponi River.

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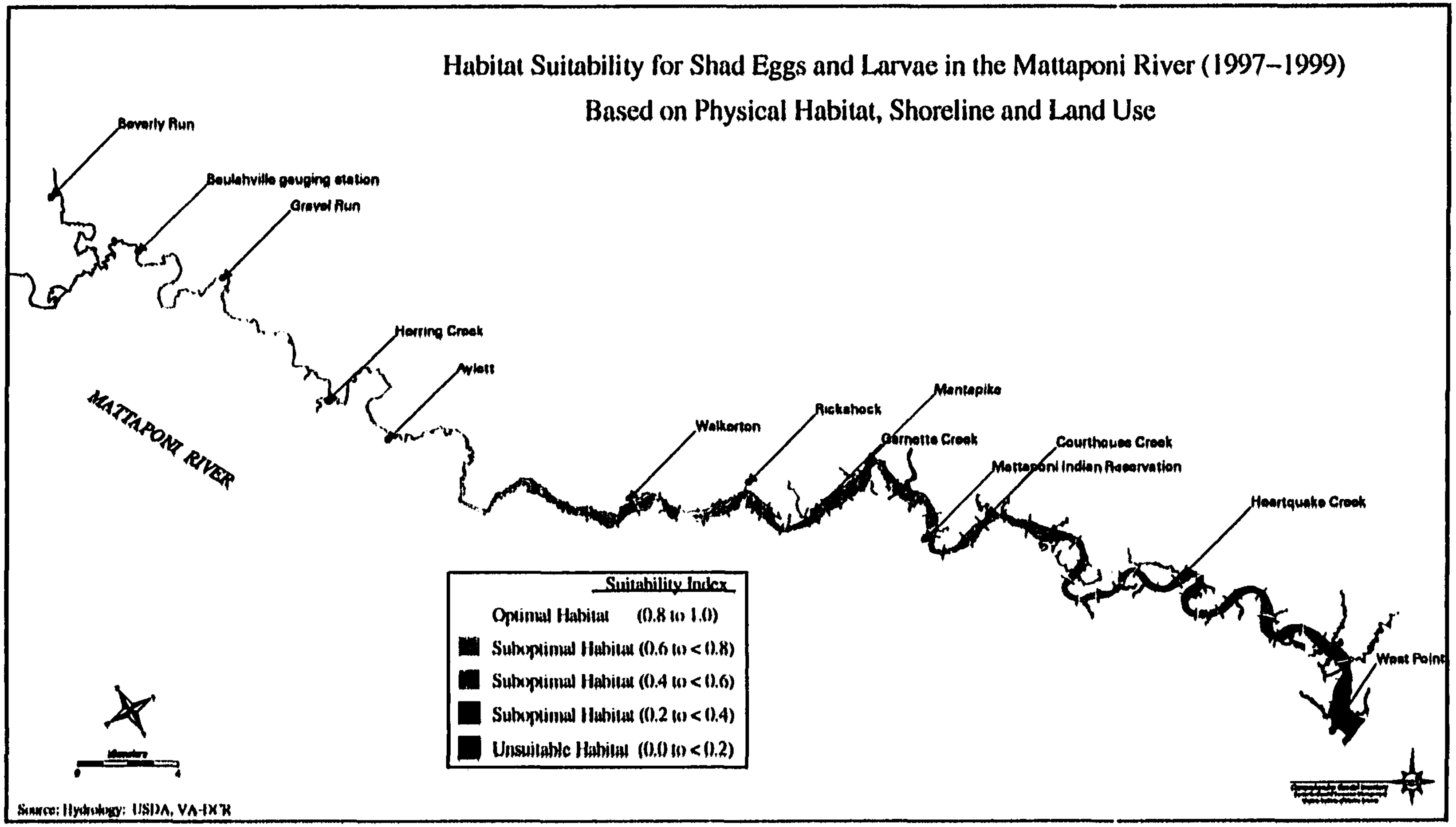

Figure 3.24. Combined habitat ratings of physical habitat, shoreline and land use features for American shad eggs and larvae in the Pamunkey River.

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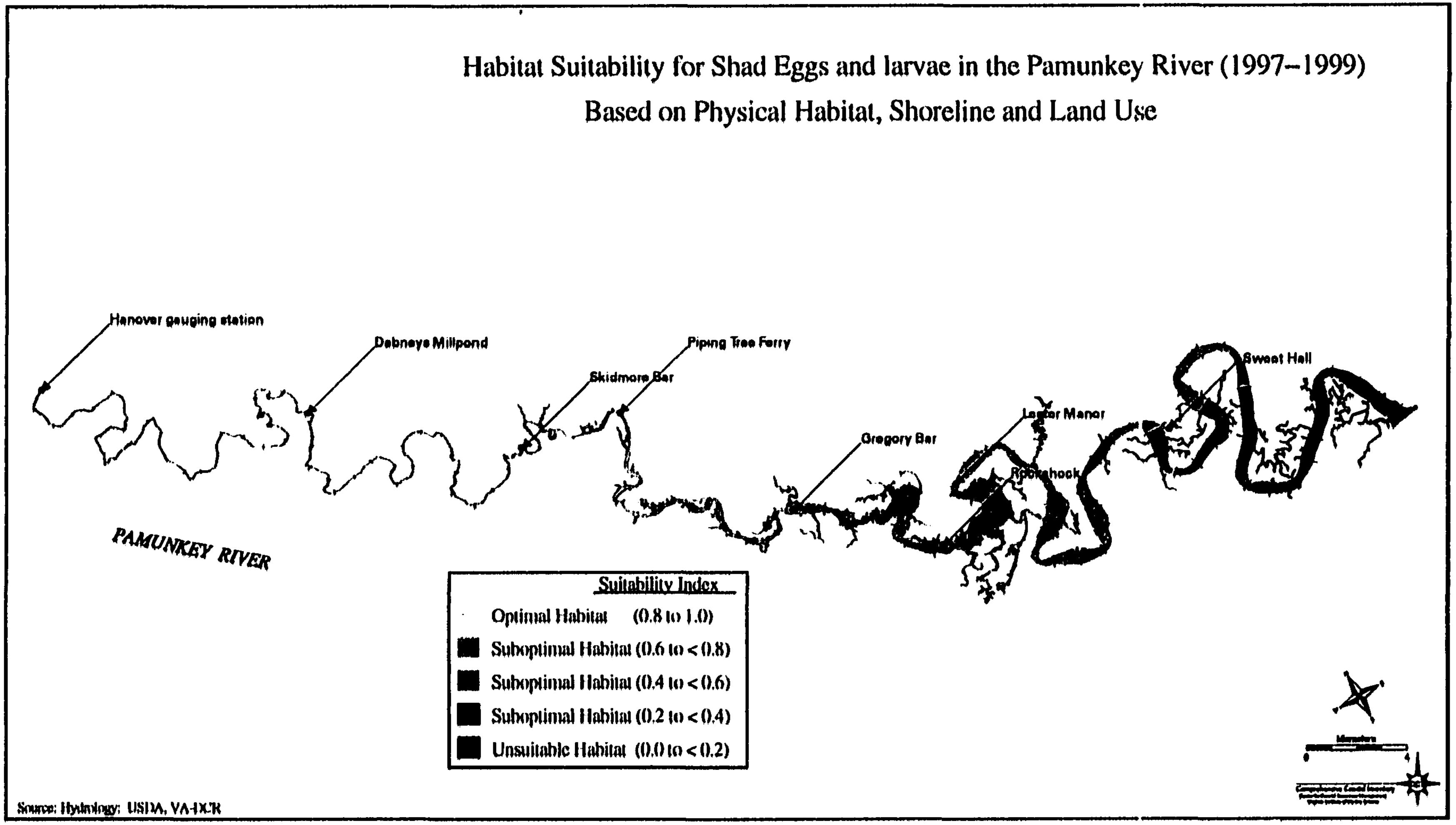

Figure 3.25. PCA plots depicting the correlation of hydrographic parameters in the Mattaponi and Pamunkey rivers (1997-1999) and the correlation of hydrographic parameters with the addition of current velocity (1998-1999). On each of the plots, 1st and 2nd principal components (PC) are depicted on the X- and Y-axis, respectively. The loadings of the parameters are illustrated with the arrows. Presence of eggs or larvae (overlaid independently on the PCA plots) is depicted with the red numbers, absence with black numbers. The numbers are kilometers from the York River, thus higher numbers are upstream. The parameter names are as follows: temp = water temperature. ph = pH. depth = channel depth, secchi = secchi depth, current = current velocity, do = dissolved oxygen.

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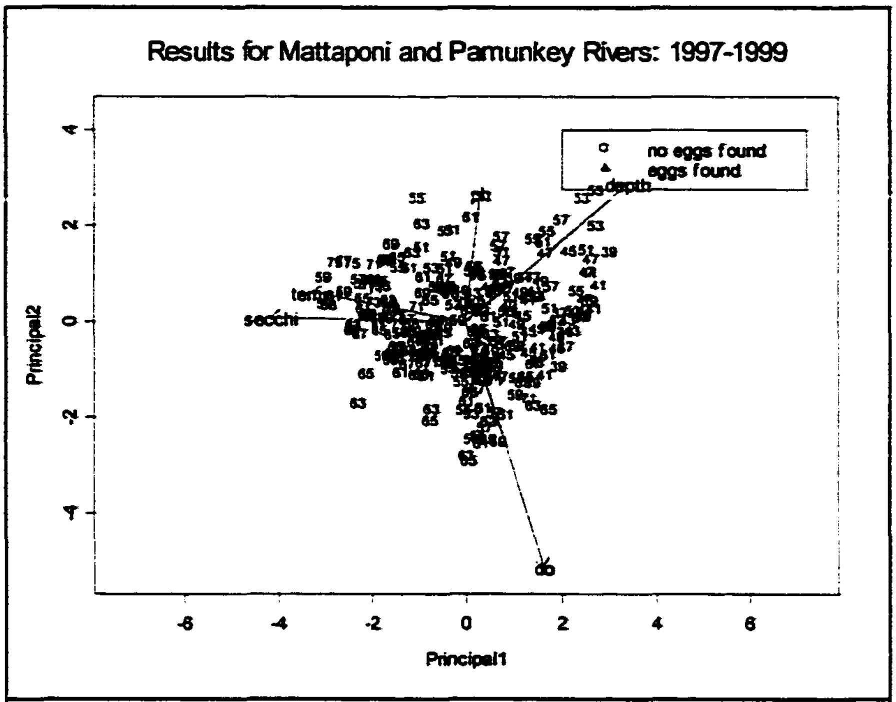

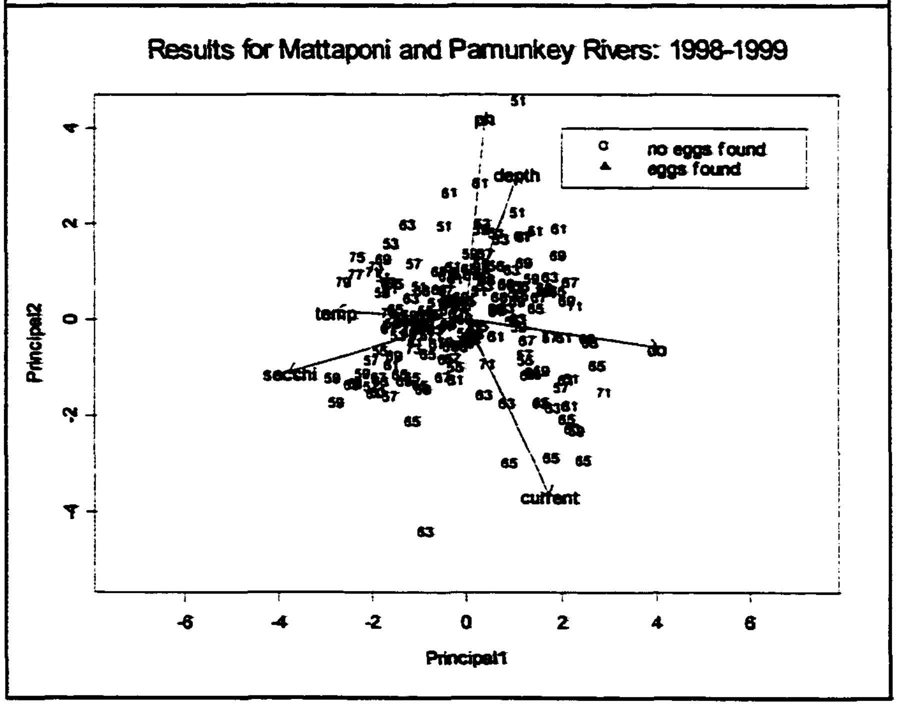

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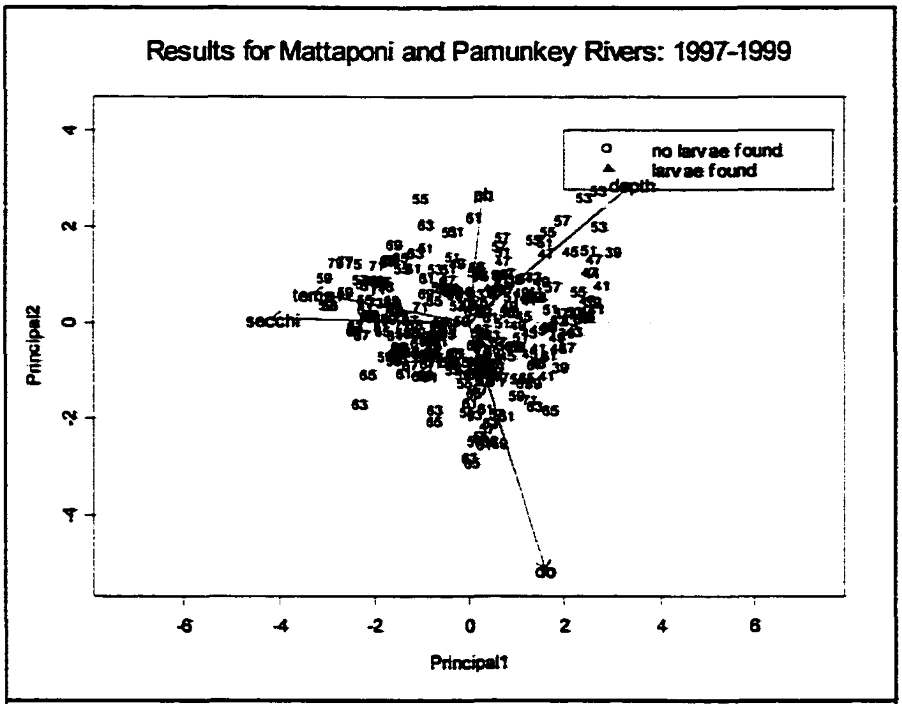

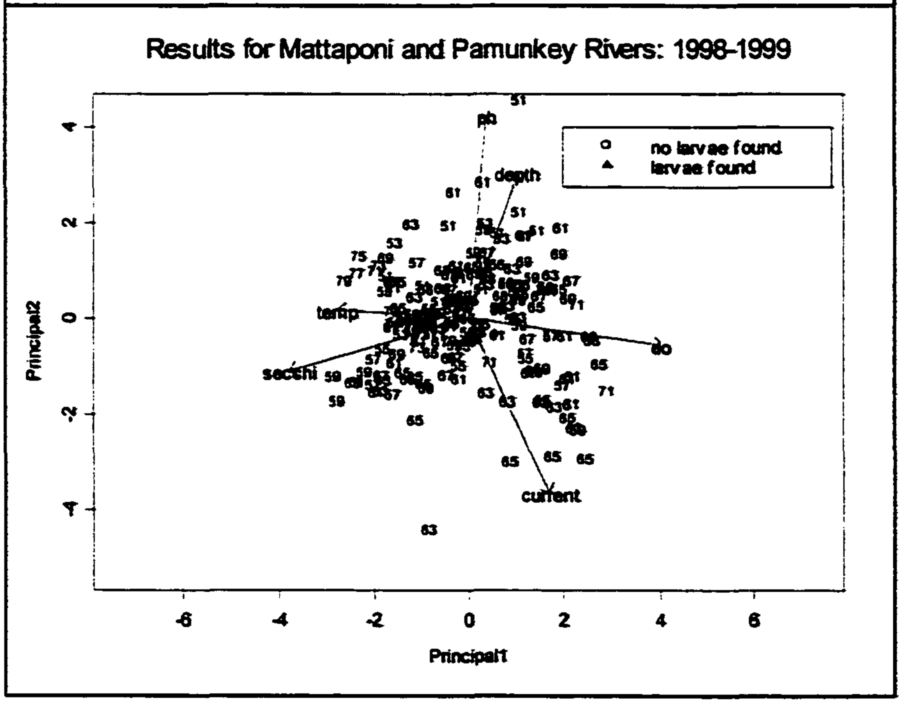

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Figure 3.26. PCA plots depicting the correlation of physical habitat features in the Mattaponi and Pamunkey rivers. On each of the PCA plots, 1st and 2nd principal components (PC) are depicted on the X- and Y-axis, respectively. The loadings of the parameters are illustrated with the arrows. Presence of eggs or larvae (overlaid independently on the PCA plots) is depicted with the red numbers, absence with black numbers. The numbers are kilometers from the York River, thus higher numbers are upstream. The parameter names are as follows: width:depth = width to depth ratio, creeks = number of creeks per reach, sinuose = sinuosity (channel distance /straight line distance), deadarea = deadfall per area, sedave = average sediment size, over = overhang.

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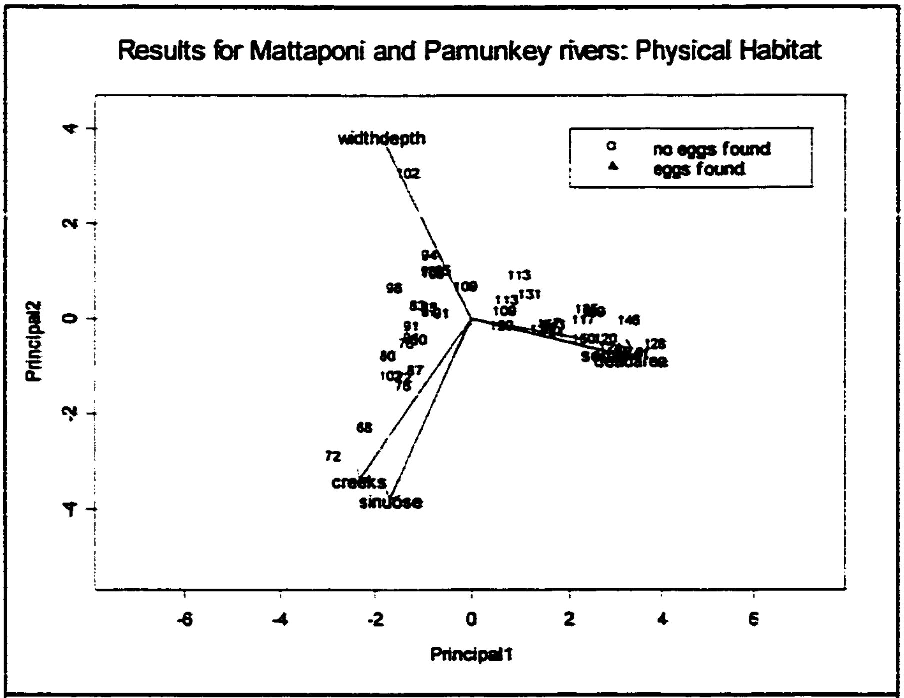

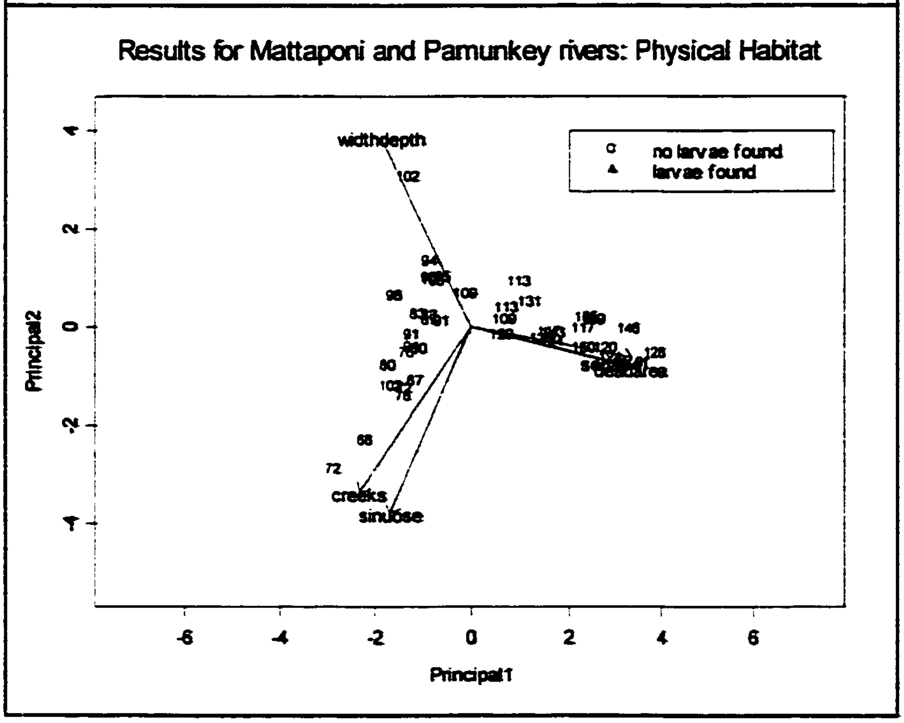

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Figure 3.27. PCA plots depicting the correlation of shoreline and land use features in the Mattaponi and Pamunkey rivers. On each of the PCA plots, 1st and 2nd principal components (PC) are depicted on the X- and Y-axis, respectively. The loadings of the parameters are illustrated with the arrows. Presence of eggs or larvae (overlaid independently on the PCA plots) is depicted with the red numbers, absence with black numbers. The numbers are kilometers from the York River, thus higher numbers are upstream. The parameter names are as follows: dev.res = percent developed and residential shoreline, dev.reslu = percent developed and residential land use, croplu = percent agricultural land use, forestshl = percent forested shoreline, forestlu = percent forested land use, eroshigh = percent high erosion, marsh = percent marsh shoreline, emergent = percent marsh land use, grasshl = percent grass shoreline.

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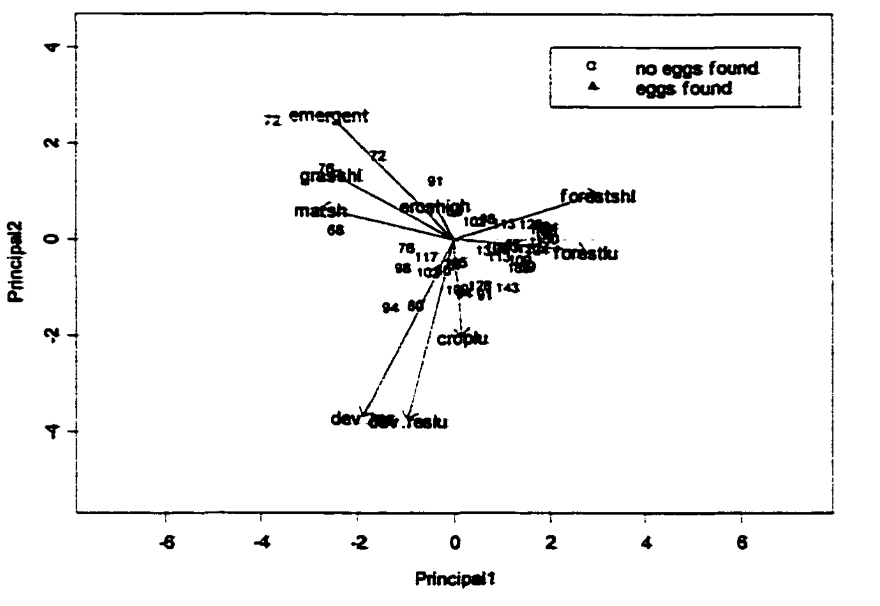
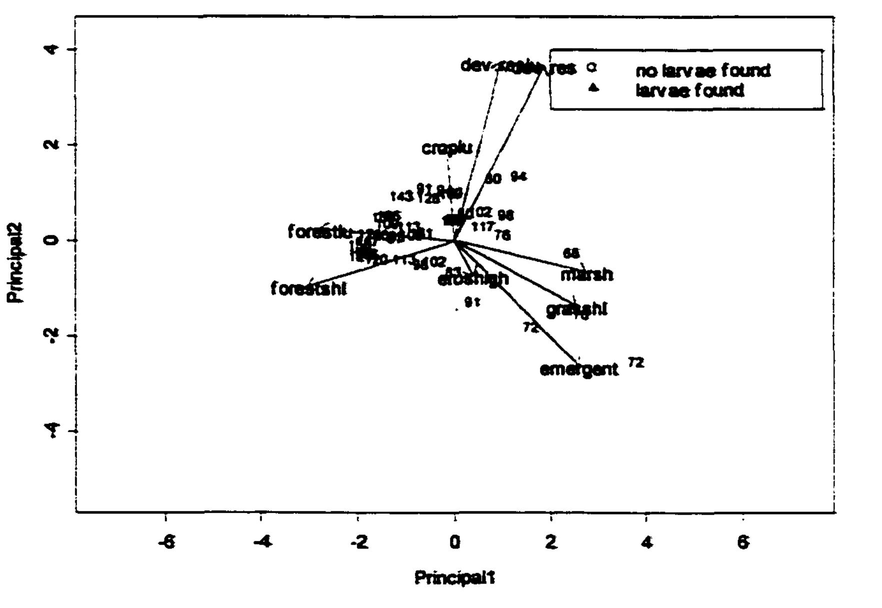
Mattaponi and Pamunkey rivers: Land Use and Shoreline



Mattaponi and Pamunkey rivers: Land Use and Shoreline



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APPENDIX I.

Binary Logistic Regressions

Hydrographic Data without Current velocity: Mattaponi and Pamunkey Rivers, 1997-99
Ia. Egg presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
eggP/A	1	57	(Event)
	0	221	
	Total	278	

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	95% CI Upper
Constant	-1.6688	0.1902	-8.77	0.000			
PC1-mp97	-0.2985	0.1353	-2.21	0.027	0.74	0.57	0.97
PC2-mp97	-0.9946	0.1822	-5.46	0.000	0.37	0.26	0.53

Log-Likelihood = -120.892
Test that all slopes are zero: G = 40.278, DF = 2, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	311.381	275	0.065
Deviance	241.784	275	0.926
Hosmer-Lemeshow	12.279	8	0.139

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	2	2	1	4	2	3	4	9	15	15	57
Exp	0.7	1.6	2.2	3.0	4.3	5.3	6.7	8.2	9.8	15.2	
0											
Obs	25	26	27	24	26	24	24	19	13	13	221
Exp	26.3	26.4	25.8	25.0	23.7	21.7	21.3	19.8	18.2	12.8	
Total	27	28	28	28	28	27	28	28	28	28	278

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	9674	76.8%	Somers' D	0.54
Discordant	2865	22.7%	Goodman-Kruskal Gamma	0.54
Ties	58	0.5%	Kendall's Tau-a	0.18
Total	12597	100.0%		

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Hydrographic Data without Current velocity: Mattaponi and Pamunkey Rivers, 1997-99
Ib. Larval presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
larvaP/A	1	69	(Event)
	0	209	
	Total	278	

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	Upper
Constant	-1.2045	0.1505	-8.00	0.000			
PC1-mp97	-0.09970	0.09906	-1.01	0.314	0.91	0.75	1.10
PC2-mp97	0.5864	0.1493	3.93	0.000	1.80	1.34	2.41

Log-Likelihood = -146.816
Test that all slopes are zero: G = 17.923, DF = 2, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	273.189	275	0.520
Deviance	293.632	275	0.210
Hosmer-Lemeshow	17.803	8	0.023

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	3	2	4	6	8	4	5	16	13	8	69
Exp	2.4	3.9	4.6	5.3	6.1	6.7	7.9	9.0	10.4	12.9	
0											
Obs	24	26	24	22	20	23	23	12	15	20	209
Exp	24.6	24.1	23.4	22.7	21.9	20.3	20.1	19.0	17.6	15.1	
Total	27	28	28	28	28	27	28	28	28	28	278

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	9664	67.0%	Somers' D	0.35
Discordant	4661	32.3%	Goodman-Kruskal Gamma	0.35
Ties	96	.0.7%	Kendall's Tau-a	0.13
Total	14421	100.0%		

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Hydrographic Data including Current Velocity: Mattaponi and Pamunkey Rivers, 1998-99
IIa. Egg presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
eggpa	1	50	(Event)
	0	138	
	Total	188	

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	95% CI Upper
Constant	-1.1597	0.1857	-6.25	0.000			
PC1-mp98	0.4687	0.1348	3.48	0.001	1.60	1.23	2.08
PC2-mp98	-0.5360	0.1611	-3.33	0.001	0.59	0.43	0.80

Log-Likelihood = -95.599
Test that all slopes are zero: G = 26.579, DF = 2, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	175.304	185	0.684
Deviance	191.199	185	0.362
Hosmer-Lemeshow	17.569	8	0.025

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	1	3	2	5	1	9	9	11	9	50
Exp	1.3	2.5	2.9	3.3	3.8	4.1	5.2	6.0	8.3	12.7	
0											
Obs	18	18	16	17	14	17	10	10	8	10	138
Exp	16.7	16.5	16.1	15.7	15.2	13.9	13.8	13.0	10.7	6.3	
Total	18	19	19	19	19	18	19	19	19	19	188

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	5279	76.5%	Somers' D	0.54
Discordant	1575	22.8%	Goodman-Kruskal Gamma	0.54
Ties	46	0.7%	Kendall's Tau-a	0.21
Total	6900	100.0%		

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Hydrographic Data including Current Velocity: Mattaponi and Pamunkey Rivers, 1998-99
IIb. Larval presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
larvpa	1	39	(Event)
	0	149	
	Total	188	

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	95% CI Upper
Constant	-1.4081	0.1908	-7.38	0.000			
PC1-mp98	-0.3407	0.1452	-2.35	0.019	0.71	0.54	0.95
PC2-mp98	0.1269	0.1620	0.78	0.434	1.14	0.83	1.56

Log-Likelihood = -92.842
Test that all slopes are zero: G = 6.285, DF = 2, P-Value = 0.043

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	183.227	185	0.523
Deviance	185.684	185	0.472
Hosmer-Lemeshow	14.632	8	0.067

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	3	2	4	8	3	6	1	4	8	39
Exp	1.6	2.3	2.8	3.3	3.8	3.9	4.5	4.9	5.4	6.4	
0											
Obs	18	16	17	15	11	15	13	18	15	11	149
Exp	16.4	16.7	16.2	15.7	15.2	14.1	14.5	14.1	13.6	12.6	
Total	18	19	19	19	19	18	19	19	19	19	188

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	3535	60.8%	Somers' D	0.23
Discordant	2208	38.0%	Goodman-Kruskal Gamma	0.23
Ties	68	1.2%	Kendall's Tau-a	0.08
Total	5811	100.0%		

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Physical Habitat Features: Mattaponi and Pamunkey Rivers
IIIa. Egg presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
eggpa	1	23	(Event)
	0	18	
	Total	41	

41 cases were used
163 cases contained missing values

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	95% CI Upper
Constant	0.2634	0.3614	0.73	0.466			
PC1-mpsh	0.4599	0.2375	1.94	0.053	1.58	0.99	2.52
PC2-mpsh	0.9193	0.4052	2.27	0.023	2.51	1.13	5.55

Log-Likelihood = -22.891
Test that all slopes are zero: G = 10.444, DF = 2, P-Value = 0.005

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	40.798	38	0.348
Deviance	45.783	38	0.180
Hosmer-Lemeshow	7.085	8	0.528

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	1	1	2	2	4	4	3	2	4	23
Exp	0.3	0.9	1.7	2.0	2.4	2.6	2.7	2.9	3.1	4.3	
0											
Obs	4	3	3	2	2	0	0	1	2	1	18
Exp	3.7	3.1	2.3	2.0	1.6	1.4	1.3	1.1	0.9	0.7	
Total	4	4	4	4	4	4	4	4	4	5	41

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	318	76.8%	Somers' D	0.54
Discordant	95	22.9%	Goodman-Kruskal Gamma	0.54
Ties	1	0.2%	Kendall's Tau-a	0.27
Total	414	100.0%		

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Physical Habitat Features: Mattaponi and Pamunkey Rivers
IIIb. Larval presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
larvalpa	1	27	(Event)
	0	14	
	Total	41	

41 cases were used
169 cases contained missing values

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	95% CI Upper
Constant	0.6721	0.3835	1.75	0.080			
PC1-mpsh	-0.6780	0.2507	-2.70	0.007	0.51	0.31	0.83
PC2-mpsh	-0.1371	0.3936	-0.35	0.728	0.87	0.40	1.89

Log-Likelihood = -21.564
Test that all slopes are zero: G = 9.516, DF = 2, P-Value = 0.009

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	42.169	38	0.295
Deviance	43.128	38	0.261
Hosmer-Lemeshow	7.182	8	0.517

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	1	1	2	3	3	3	3	4	2	5	27
Exp	1.0	1.4	1.8	2.3	2.7	3.1	3.2	3.4	3.5	4.6	
0											
Obs	3	3	2	1	1	1	1	0	2	0	14
Exp	3.0	2.6	2.2	1.7	1.3	0.9	0.8	0.6	0.5	0.4	
Total	4	4	4	4	4	4	4	4	4	5	41

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	288	76.2%	Somers' D	0.53
Discordant	87	23.0%	Goodman-Kruskal Gamma	0.54
Ties	3	0.8%	Kendall's Tau-a	0.25
Total	378	100.0%		

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Shoreline and Land use data: Mattaponi and Pamunkey Rivers
IVa. Egg presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
eggpa	1	23	(Event)
	0	17	
	Total	40	

40 cases were used
142 cases contained missing values

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	Upper
Constant	0.0769	0.3731	0.21	0.837			
PC1-mpsh	0.7359	0.3096	2.38	0.017	2.09	1.14	3.83
PC2-mpsh	0.0883	0.4781	0.18	0.853	1.09	0.43	2.79

Log-Likelihood = -23.610
Test that all slopes are zero: G = 7.329, DF = 2, P-Value = 0.026

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	39.677	37	0.352
Deviance	47.220	37	0.121
Hosmer-Lemeshow	9.267	8	0.320

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	1	3	2	2	4	2	3	4	2	23
Exp	0.6	1.3	1.8	2.1	2.3	2.6	2.8	3.0	3.2	3.3	
0											
Obs	4	3	1	2	2	0	2	1	0	2	17
Exp	3.4	2.7	2.2	1.9	1.7	1.4	1.2	1.0	0.8	0.7	
Total	4	4	4	4	4	4	4	4	4	4	40

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	276	70.6%	Somers' D	0.41
Discordant	114	29.2%	Goodman-Kruskal Gamma	0.42
Ties	1	0.3%	Kendall's Tau-a	0.21
Total	391	100.0%		

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Shoreline and Land use data: Mattaponi and Pamunkey Rivers
IVb. Larval presence: PC1 and 2 scores

Link Function: Logit
Response Information

Variable	Value	Count	
larvalpa	1	27	(Event)
	0	13	
	Total	40	

40 cases were used
142 cases contained missing values

Logistic Regression Table

Predictor	Coef	StDev	Z	P	Odds Ratio	95% CI Lower	Upper
Constant	2.3030	0.9227	2.50	0.013			
PC1-mpsh	-1.6853	0.6542	-2.58	0.010	0.19	0.05	0.67
PC2-mpsh	1.1280	0.9364	1.20	0.228	3.09	0.49	19.36

Log-Likelihood = -18.354
Test that all slopes are zero: G = 13.739, DF = 2, P-Value = 0.001

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	32.382	37	0.685
Deviance	36.707	37	0.483
Hosmer-Lemeshow	4.040	8	0.853

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

Value	Group 1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	2	0	2	2	3	3	3	4	4	4	27
Exp	1.2	1.4	1.6	2.1	2.6	3.0	3.5	3.7	3.9	4.0	
0											
Obs	2	4	2	2	1	1	1	0	0	0	13
Exp	2.8	2.6	2.4	1.9	1.4	1.0	0.5	0.3	0.1	0.0	
Total	4	4	4	4	4	4	4	4	4	4	40

Measures of Association:
(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	290	82.6%	Somers' D	0.66
Discordant	58	16.5%	Goodman-Kruskal Gamma	0.67
Ties	3	0.9%	Kendall's Tau-a	0.30
Total	351	100.0%		

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Chapter 4

Hydrodynamic influences on American shad (*Alosa sapidissima*) in the Mattaponi and Pamunkey rivers

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Abstract

Anadromous fishes are subjected to mutable conditions during migration, reproduction and development that may shape recruitment. In particular, recruitment levels of anadromous fishes are thought to be sensitive to fluctuating hydrographic and meteorological conditions. Density-independent factors are not the sole controls over juvenile *Alosa* survival, but they may play an important role in the evolution of stocks. Abiotic factors may impact spawning location, transport of larvae, development rates and predator and prey abundance. Understanding abiotic influences over recruitment will aid in restoration of anadromous fishes, as well as supplement habitat studies that must consider fluctuations in spawning and nursery zones. Responses to hydrographic conditions in two natural river systems (Mattaponi and Pamunkey rivers) by American shad (*Alosa sapidissima*), and the effects of discharge on larval transport and habitat exposures were examined. Utilizing the juvenile *Alosa* index (JAI) from 1991-1999 as an estimate of juvenile shad recruitment, correlation with hydrographic parameters was examined. For each of the months during spawning to the onset of juvenile sampling (March, April, May and June), the mean, minimum, and maximum discharge, total monthly precipitation and average monthly water temperature were correlated with the natural log of juvenile shad indices for the Mattaponi and Pamunkey rivers. To further explore the influence of interannual variable flow, correlation between the number of days discharge was within 25% and 75% quartiles per month and JAI were determined. Interrelationships between hydrographic parameters were also noted. Hydrographic conditions during May and June appear to most accurately predict patterns in juvenile recruitment in the Mattaponi River, however trends in the Pamunkey River were not as consistent. Because of the inconsistency in hydrographic controls between rivers, other possible influences were explored, including biotic, morphological, and water quality. Ultimately, discharge affects transport of weak-swimming early larva to variably favorable nursery habitats. I used a hydrodynamic model to hypothesize potential impacts of variable habitat exposures on larvae that are distributed by discharge.

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Introduction

The complicated life history of anadromous fishes makes it difficult to ascribe specific controls on recruitment. Anadromous fishes encounter a series of abiotic and biotic hurdles during their spawning migration runs, development, growth and outmigration that may hinder survival. While determining primary influences on anadromous populations has proven to be difficult, several researchers have demonstrated the importance of hydrographic and meteorological factors on spawning and juvenile recruitment (Leggett and Whitney 1972; Stevens and Miller 1983; Crecco and Savoy 1984; Crecco and Savoy 1987b; Rulifson and Manooch 1990). Leggett and Whitney (1972) authenticated strong correlation between water temperature and the timing of American shad (*Alosa sapidissima*) spawning migrations along the East Coast, with peak runs occurring from 15.5 – 20.0°C. Extreme high and low May flows (> 283 m^3/s and <142 m^3/s) in the Roanoke River, North Carolina, were associated with low striped bass (*Morone saxatilis*) juvenile indices (Rulifson and Manooch 1990). High discharge, high precipitation, and low water temperature have been negatively correlated with American shad juvenile abundance, while low discharge, low precipitation and high temperatures were correlated with high juvenile abundance in the Connecticut River (Crecco and Savoy 1984). In the Hudson River, the American shad year-class was established mainly by cohorts spawned late in the season (June) with declines in flow, and increases in temperature and zooplankton levels, whereas most spawning activity occurred in early to mid-May (Limburg 1996). However, each river system is unique and simple comparisons among systems are often invalid. Annual and inter-annual variations in discharge, variations in spawning location and habitat suitability also confound recruitment predictions. While it

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may be possible to delineate optimal spawning and nursery habitats for anadromous fishes, their life history makes it necessary to consider variations in flow, spawning location, population size, and habitat. Once hydrographic influences on larval survival and transport, are better understood, variable habitat suitability models may be employed which describe the subsequent habitat, including prey availability and predator abundance experienced by larvae.

Declines in populations of anadromous fishes have often been attributed to habitat loss due to water control structures, which eliminated or altered spawning habitat. American shad populations have been affected along the East Coast by habitat loss and flow alterations, and subsequent declines have led to moratoria in some areas (Mansueti and Kolb 1953; Walburg and Nichols 1967; Carlson 1968; ASMFC 1999). To fully comprehend the impact of human-induced flow alterations on anadromous fishes, the impact of natural flow variation needs to be addressed for each system. An understanding of the impacts of natural variations in flow on survival may then aid in the designation of flow requirements for altered channels. In Virginia, the Mattaponi and Pamunkey rivers support the two strongest runs of American shad (Olney and Hoenig 2000). Migration runs have not been blocked and flow has not been altered in these rivers. A recent proposal to construct a reservoir, which would alter flows and habitat throughout the Mattaponi and Pamunkey watersheds, has raised questions of the impact of water withdrawal on American shad populations.

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To gain a better understanding of potential hydrographic influences on American shad populations in the Mattaponi and Pamunkey rivers, this study included three objectives: 1) to examine differences in discharge between the two rivers, 2) to correlate annual indices of abundance of juvenile shad to a variety of flow parameters for both rivers, and 3) to simulate varying discharge, spawning locations and habitat suitability using a hydrodynamic model.

While hydrographic parameters are hypothesized to affect shad populations in these two river similarly due to their geographic closeness and similar physiography, differences in historic mean recruitment (1991-1999) between the rivers exist (Mattaponi JAI, 1522.6; Pamunkey JAI, 247.0). Thus, other river-specific influences which have the potential to impact recruitment of shad were addressed, including water quality, prey and predator abundance, river morphology and land use.

Study Site

The York River is formed by the confluence of the Mattaponi and Pamunkey rivers. The Pamunkey River has a larger watershed and higher average discharge (3768 km^2 and 29.2 m^3/s) than the Mattaponi River (2274 km^2 and 16.7 m^3/s). The lengths of the Mattaponi and Pamunkey rivers from the confluence with the York River to the fall lines are approximately 85 and 125 km, respectively (Table 4.1). The fall line is denoted by the location of U.S. Geological Survey (USGS) gauge stations and is considered to be the furthermost limit of tidal influence. On the Pamunkey River, a bypass reservoir (Lake Anna), located above the fall line, has been in operation under Virginia Power since

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1978. Virginia Power is required to maintain flows at a minimum of 40 cfs from the reservoir (approximate historic low flows at the dam site), thus the reservoir is not thought to have an impact on the hydroperiod. However, since the inception of the reservoir, downstream consumptive use has increased which has an indeterminate impact during extreme drought periods on flows. Consumptive use for 1990 was estimated to average 34.2 mgd on the Pamunkey River and 3.1 mgd in the Mattaponi River, which does not contain a comparable reservoir to Lake Anna (Norfolk District Army Corps of Engineers 1997). While consumptive use may slightly alter natural flow, the impact is most likely minimal during non-drought conditions due to low average consumptive use, and the systems may be considered natural flow rivers. The Mattaponi and Pamunkey watersheds are dominated by forest (66.7, 63.2%, respectively) and agriculture (15.2, 15.3%, respectively) land use (Table 4.1; see chapter 3).

Methods

Discharge comparisons

Discharge data were obtained from USGS stream gauge stations located approximately at the fall lines of the Pamunkey and Mattaponi rivers, (Hanover station (#01673000); Beulahville station (#01674500), respectively). Corrected data is available from 1941 through September 1999, with the exception of missing discharge information for 1988 and 1989 in the Mattaponi River. A two-sample t-test was used to test for significant differences between annual mean, and monthly mean discharge values of March, April, May and June for the Mattaponi and Pamunkey rivers.

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Juvenile* Alosa *Index and Discharge

The *Alosa* Monitoring Program at the Virginia Institute of Marine Science (VIMS) has conducted juvenile *Alosa* collections and determined juvenile *Alosa* indices (JAI) for the Pamunkey and Mattaponi rivers since 1979 with one interruption between 1989-1990 (Olney and Hoenig 2000). Sampling protocols prior to 1991 varied; thus, indices from 1991 until present were used for comparisons. Geometric means and areas under the catch curve for American shad were estimated from cruise-specific catch rates for each year. The indices calculated from areas under the catch curves were compared to discharge data. Discharge data was taken from the months that encompassed shad spawning and larval development through the start of sampling for juvenile abundance (March-June). Correlations between mean, minimum and maximum March, April, May and June discharge and the natural log of juvenile shad indices were examined. Trends between the annual index data and discharge were further described using simple linear regression analysis with the juvenile annual index as the dependent variable and discharge as the independent variable. To further explore the influence of interannual variable flow, correlation between the number of days discharge was within 25% and 75% quartiles per month, and JAI were determined. Historic long-term discharge data from 1941 to 1999 were used to estimate 25 and 75% quartiles. In all cases, discharge was compared with the log of juvenile indices using Pearson correlation. Correlation coefficients and significance were calculated for each correlation. The natural log of the American shad juvenile index was used to minimize variability among the annual indices. Spurious correlation was possible due to the inter-relationships of hydrographic parameters between months during the same years, thus the results were merely used as a

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guide to potentially important periods (Stevens and Miller 1983; Walters and Collie 1988).

Precipitation and Water Temperature

Total monthly precipitation and average monthly water temperature were also compared with annual indices of abundance of juvenile shad for the months of March-June (Pearson correlation). Precipitation data for the state of Virginia was obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/ol/ncdc.html), and water temperature was obtained from the VIMS Ferry Pier Ambient Monitoring Data located at the mouth of the York River in Gloucester Point, VA (http://www.vims.edu/data_archive/pier/). Daily discharge, water temperature and precipitation in the Mattaponi and Pamunkey rivers were plotted separately by year (1991-1999) to examine small-scale fluctuations in hydrographic parameters that may impact survival of early life stages.

Zooplankton Collections

Prey availability was examined by enumerating zooplankton community assemblages from ichthyoplankton collections in the Mattaponi and Pamunkey rivers (1997-1999). Sampling methods are described in Chapter 1. In all years, two 60 cm diameter bongo net of 333 μm mesh were used; therefore, only adult mesoplankton could be enumerated. Specimens were placed into four general categories: copepods, cladocerans, aquatic insects and crustaceans. Predominant groups included bosminids, daphnids, and the adult stages of cyclopoid and calanoid copepods. Samples were rinsed of Formalin, diluted to a known volume, and subsampled for enumeration. Plankton density (#/m^3) was

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estimated by dividing the number of specimens in the total sample by an estimate of the volume of water filtered.

Hydrodynamic model

Sisson et al. (1997) have developed a multi-parameter finite difference model, which integrates hydrodynamic, sediment transport, and water quality models. A vertically averaged rendition of this model incorporates tidal heights, current speed and direction, and discharge to produce probability estimates of shad egg and larval dispersal. This model is conceptual in that it attempts to combine a number of factors that may influence recruitment to the juvenile population in the Mattaponi and Pamunkey rivers. These include spawning location, river flow, river temperature (time to hatching), and relative habitat suitability of individual river sections. The model is based on the dispersion of eggs and larvae by river hydrodynamics. Three different spawning locations in each river (Figure 4.1) are simulated under three river discharge conditions (selected to represent high, medium, and low flow conditions typical for the spawning season in these rivers based on the calculation of 14-day moving averages, and the ninety and ten percentiles of April discharge) (Table 4.2). The increment of fourteen days was chosen to encompass spawning, hatching and early larval stages, which are primarily dependent on hydrodynamics for transport. The ninety and ten percentiles were used to represent high and low flows, but not extreme events. Discharge data was obtained from USGS Water Resource Division stream gauge information at the fall lines of the Mattaponi and Pamunkey rivers (Beulahville, Hanover, respectively) over the time period 1979-98, which corresponds to the collection of juvenile indices data. Release of eggs was

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modeled from the river bottom and the particles were neutrally buoyant to mimic shad eggs. The settling velocity used was 10^{-4} m/s, which closely corresponds to reported settling velocities of shad eggs (Massmann 1952; Chittenden 1969). The model allows for partitioning of the spawning effort among the three locations (by percentage of total effort). Distribution of the eggs/larvae is then simulated for 30 successive tidal cycles (approximating a 14-day interval). Each river is divided into an upstream, mid-river, and downstream section based on morphological and habitat parameters sampled for this study (see chapter 3). Each river section can than be assigned a relative habitat value for eggs, and a relative habitat value for larvae. The effect of temperature on egg maturation is simulated by selecting a tidal cycle at which eggs become larvae, and the habitat value attributed to larvae is applied for subsequent tidal cycles. For instance, in cold temperatures, maturation is slowed and time to hatching into a larval stage occurs at a later tidal cycle than in warm temperatures. The habitat values are hypothetical, and have significance only in relation to one another. Final index values describe a population's cumulative habitat experience over 30 tidal cycles. Index value ranges are dependent on the habitat value applied. If habitat values are held constant in scenarios within the same river system, then comparison between scenarios is valid. The intent is to simulate the cumulative experience of the population of propagules as it is advected through river sections of differing suitability.

For the purposes of demonstrating the capabilities of the hydrodynamic model two sets of scenarios were completed. The first set depicts the index values derived for population habitat experience under two different scenarios of habitat suitability values. For both

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scenarios spawning is assumed to be spread evenly among the three potential release sites on each river, and time of egg hatching is set at tidal cycle 20 (of 30). In scenario 1, habitat suitability is assumed to be equal and moderate in all river sections. In scenario 2, habitat suitability is assumed to be higher in upstream and mid-river sections for eggs, and higher in mid and downstream river sections for larvae (the basic hypothesis developed in this study, see Chapter 3).

The second set of scenarios describes index values derived for population habitat experience under three different spawning release sites. For all scenarios, habitat suitability is assumed to be higher in upstream and mid-river sections for eggs, and higher in mid and downstream river sections for larvae. Time of egg hatching is set at tidal cycle 20 (of 30). In scenario 1, spawning primarily occurs in upstream and mid-river sections. In scenario 2, spawning is assumed to be spread evenly among the three potential release sites on each river. In scenario 3, spawning primarily occurs in mid and downstream river sections.

Additional Data Sources

Land use percentages were calculated from Multi-Resolution Land Use Characterization (MRLC) data from Environmental Protection Agency (EPA) Region III Land Cover Data set, 1996 (TM data from 1992-94 using the combined resources of EPA, United States Geological Survey (USGS) and National Oceanic and Atmospheric Administration (NOAA)). Surface hydrology was generated by the Comprehensive Coastal Inventory Laboratory, VIMS and provided by the U.S. Census Bureau via Topologically Integrated

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Geographic Encoding and Referencing (TIGER) system files (1991). Average seasonal dissolved oxygen (DO) and surface pH were determined from measurements during 1997-1999 shad spawning periods at 3.2 km intervals over the entire length of the rivers. Water quality data (March-June 1990-1998) was obtained from the Chesapeake Bay River Input Monitoring Program (USGS, http://va.water.usgs.gov/chesbay/RIMP).

Results

Discharge Comparison of Mattaponi and Pamunkey Rivers

Initial comparisons of river discharge from 1941 through 1999 indicate consistently higher discharge and more inter-annual variability in the Pamunkey River than the Mattaponi River. The averages (Pamunkey River = 29.2 m^3/s; Mattaponi River = 16.7 m^3/s) of long term discharge data are significantly different (2-sample t-test, $p < 0.0001$) between rivers (Figure 4.2). Likewise, March, April, May and June average discharge values (1941-1999) in the Pamunkey River were significantly higher than Mattaponi River values (2-sample t-test, $p < 0.001$). Discharge values in 1997 were similar to the long-term average for March, April and June with higher than average values in May. In both rivers, average discharge in 1998 was consistently higher than the long-term average for March through May, with similar to average values in June. In 1999, discharge values were typically lower than long-term averages in April, May and June with close to long-term averages in March (Figure 4.3).

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Juvenile index (1991-1999) and hydrographic variables

Pearson correlation comparisons of river discharge data (Tables 4.3-4.4) in relation to the juvenile annual index (JAI) for American shad indicate positive correlation between the JAI and the following: May and June mean discharge; March, May, and June minimum discharge; and May maximum discharge in the Mattaponi River. In the Pamunkey River the only evident significant correlation was a negative relationship between May mean discharge and Pamunkey River JAI (Table 4.5, Figures 4.4-4.6). In cases where significant relationships occurred, regression equations explained 41.3% to 66.0% of the variance (Table 4.6).

April precipitation (Table 4.7) was significantly related to the JAI in the Mattaponi River and June water temperature was positively correlated to the JAI in the Pamunkey River (Table 4.8). In all other cases, total monthly precipitation and mean monthly temperature for shad spawning and nursery periods (March-June) were not significantly correlated with the JAI for the Mattaponi and Pamunkey rivers.

Examination of possible interrelationships between March-June discharge, water temperature and precipitation elucidated potential correlation among the hydrographic parameters. In the Mattaponi River, March total precipitation was positively correlated with March mean discharge and April total precipitation was positively correlated with May and June mean discharge. In the Pamunkey River, no correlation was apparent between precipitation and discharge, and water temperature and discharge. The location of the temperature gauge at the mouth of the York River may be a possible reason for

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lack of correlation between temperature and discharge (Table 4.9). Fluctuations in water temperature due to discharge at the fall line may not always be evident at the temperature gauge which is located approximately 139 (Mattaponi River) and 180 (Pamunkey River) kilometers downstream of the fall lines. However, regression analysis between water temperature data obtained from the Ferry Pier gauge and the shad spawning grounds on the Pamunkey River in 1998 indicates a close relationship between these data sets ($P < 0.001$, $R^2 = 0.79$), thus overall trends should be similar (Aiken in prep)

A decreasing number of extreme discharge events (increased number of days between 25 and 75% quartiles) is correlated with high JAI in the Mattaponi River (Table 4.10). Examination of days within the 25% and 75% historic discharge quartiles (Table 4.11) indicate significant correlation with the number of days in May and June and JAI for the Mattaponi River (Table 4.10). There were no significant relationships evident in the Pamunkey River (Table 4.10).

Comparisons of daily water temperature, discharge and precipitation during 1991-1999 between the Mattaponi and Pamunkey rivers indicate that the Pamunkey River has more variation in discharge due to steep responses to precipitation events. Additionally, lag responses to some precipitation events were observed to be larger in the Mattaponi River than the Pamunkey River by 1-2 days (Figures 4.7-4.15).

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Zooplankton results

Since collections did not target the same reaches each year, zooplankton enumeration can only be used as a crude measure of community composition in each river. Overall, mesozooplankton counts and communities were similar between the Mattaponi and Pamunkey rivers. Although copepod abundance was higher in the Mattaponi River than the Pamunkey River, it was not significantly higher (Mann-Whitney, $p = 0.11$) (Figure 4.16). Aquatic insects and crustaceans were found in relatively low abundance in comparison to copepods and cladocerans.

Hydrodynamic model results

For all scenarios, habitat experience index values decrease with increasing flow (Tables 4.12-4.13). In general, egg and larval dispersal in low flow conditions is more limited than in high discharge conditions. Since the habitat values are hypothetical, and have significance only in relation to one another, the results are only comparable in each scenario and not between scenarios. Sensitivity analysis of the model results indicates a potential deviation by ±5-6. Typically, the model results indicated low and average flow values contributed to high relative habitat experience values for a population, while extreme high flows decreased these values and advected larvae from the systems into the York River. The largest declines in index values due to high flows occurred in scenarios with postulated higher habitat suitability in upstream and mid-river segments, as was hypothesized based on the presence of shad eggs (Chapters 1 and 3, Table 4.12). Upstream and mid-river spawning locations produced higher index values than scenarios with spawning in all three sections or spawning in mid and downstream sections only

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(Table 4.13), which coincided with observed shad egg distribution in 1997-1999 (See Chapter 1).

Discussion

Although the Mattaponi and Pamunkey rivers are geographically close, average annual discharge in the Pamunkey River (29.2 m^3/s) is approximately 1.7 times larger than the Mattaponi River (16.7 m^3/s). The difference in magnitude of discharge between these two systems may be explained by the nearly linear relationship observed between drainage area and discharge (Leopold 1994). The Pamunkey River drains an area (3768 km^2) 1.7 times larger than the Mattaponi River (2274 km^2), which accounts for discharge differences.

There are distinctions in discharge patterns between the two rivers aside from magnitude of discharge and drainage area. The Mattaponi River has less variation in discharge and longer lag responses to some precipitation events than the Pamunkey River (Figures 4.7-4.15). Potential reasons for the differing responses may be varying storage capabilities and precipitation exposures. The Pamunkey River watershed is larger and has an increased potential to experience precipitation events. The Mattaponi River watershed has a larger percentage of wetlands than the Pamunkey watershed (8%, 6%, respectively), which may enhance water residence time and storage and lead to longer lag responses to precipitation events. It is possible that increased variation in discharge, which increases the probability of the occurrence of extreme events, may impact the early life stages of American shad. Although this hypothesis is supported in the Mattaponi River

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(correlation between increased days within 25% and 75% quartiles and JAI), it is not supported in the Pamunkey River where variable flow effects should be heightened. However, the JAI in the Pamunkey River is much lower compared to the Mattaponi River, which may indicate some impact from discharge variation. While discharge variation may impact early life history of American shad, a clear relationship cannot be ascribed, and other river-specific influences must be considered.

Results of monthly comparisons of mean, minimum, maximum, and within 25% and 75% quartiles discharge suggest that hydrographic conditions during the month of May have the most impact on juvenile shad recruitment in the York River system. In the Mattaponi River, throughout all comparisons, May and June values were always significantly correlated with the JAI, with the exception of June maximum discharge. Although only one correlation was apparent in the Pamunkey River, it was between mean May discharge and the JAI. Strong support for climatic controls over juvenile shad recruitment was not evident from water temperature and precipitation correlation with JAI (Table 4.6). In neither the Mattaponi nor the Pamunkey rivers were consistent trends observed between climatic variables during the spawning and nursery months of American shad and the subsequent JAI. However, a positive correlation between April precipitation and May and June discharge with the Mattaponi River JAI lends support to the potential importance of hydrographic conditions in May-June to recruitment. Further support is indicated by higher percentages of juveniles with late hatch dates (May-June) than with earlier hatch dates in juvenile surveys (1998-1999) (Aiken in prep).

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Additionally, the year with the lowest JAI for both rivers (1992) had drops in May temperatures below 15°C, which may have induced mortality resulting in the subsequent low juvenile recruitment (Figure 4.9). Years with the highest JAI (1996, 1998) had consistent temperature increases during May, which remained above 15°C. In support of this proposed relationship, Leach and Houde (1999) observed little growth or production of shad larvae at 15°C, regardless of pH or prey level, and speculated that temperatures greater than 20°C were optimal. Similarly, storm-induced temperature drops below 12°C resulted in episodic mortalities of striped bass eggs and newly hatched larvae and exposures to temperature consistently greater than 17°C selected for survival of cohorts in the Chesapeake Bay (Rutherford and Houde 1995).

Disparate correlation patterns between the Mattaponi and Pamunkey rivers suggest that discharge, temperature and precipitation are not the sole controls over recruitment. Other river-specific influences may override hydrographic controls or combinations of other unknown variables may dictate juvenile survival. Alternatively, it may be possible that the JAI is not an accurate portrayal of recruitment success and thus patterns are masked. However, a recent study shows strong agreement between the JAI and an independent seine survey, suggesting that the JAI accurately measures annual trends in abundance (Aiken in prep). Thus, the JAI is likely a reliable indicator of juvenile production in river systems. An additional consideration is that comparison of monthly hydrographic parameters with an annual JAI may miss the impact of small-scale fluctuations on survival, leading to incorrect conclusions (Crecco and Savoy 1987b).

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It is also difficult to make comparisons between the Mattaponi and Pamunkey rivers and larger systems where there has been success in linking hydrographic parameters with American shad recruitment. It may be that in systems with large watersheds, and high discharge during spawning events (>100 m^3/s), such as the Connecticut River, hydrographic parameters become driving influences over recruitment. In smaller systems (e.g., the Mattaponi and Pamunkey rivers) that experience lower discharge levels and fewer extreme events, additional biotic and abiotic factors may have stronger influences on the growth and survival of the early life stages of shad.

Mean recruitment of American shad (1991-1999) was higher on the Mattaponi River than the Pamunkey River (Mattaponi JAI, 1522.6; Pamunkey JAI, 247.0) (Aiken in prep.; Bilkovic et al. in review). The difference in JAIs indicates potential differential juvenile survival. Alternatively, differential spawning, or egg and larval survival may occur because reduced, more consistent flow in the Mattaponi River is preferred to the Pamunkey River. Discharge may be a contributing factor to these differences, but since no clear relationship exists between discharge and the Pamunkey River JAI other factors should be considered. Thus, potential factors (i.e., water quality, sinuosity, land use and biotic) that may impact the early life stages of shad are discussed below.

Nutrient and turbidity differences

Potential water quality influences on juvenile survival were examined with March-June 1990-1998 data from the Chesapeake Bay River Input Monitoring Program (USGS, http://va.water.usgs.gov/chesbay/RIMP). While nitrogen (ammonia and organic

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nitrogen) and total phosphorus measured at USGS fall line stations indicated similar long-term spring averages (1990-1998) between the Mattaponi and Pamunkey rivers (Nitrogen (0.47, 0.46 mg/L); Phosphorus (0.06, 0.07 mg/L), respectively), yields of total nitrogen, phosphorus and suspended solids (1985-1996) are higher on the Pamunkey River. This may be due to the larger percentage of Piedmont Crystalline litho-physiographic region (LPR) in the Pamunkey River sub-basin above the fall line as opposed to the Mattaponi River sub-basin (93%, 38.7%, respectively). The larger percentage of Coastal Plain LPR in the Mattaponi River sub-basin than the Pamunkey River sub-basin, results in lower stream gradients and channel velocities and thus smaller suspended loads (Johnson and Belval 1998) (Table 4.1). Likewise, suspended carbon measured from 1995-1999 was found to be slightly higher in the Pamunkey River than Mattaponi River (0.82, 0.68 mg/L, respectively). Higher concentrations of average dissolved silica in the Pamunkey River than the Mattaponi River (10.2, 6.5 mg/L, respectively), may sustain higher microplankton communities (primarily diatoms which extract and use silica in their shells and skeletons) in the Pamunkey River (Table 4.1). Unfortunately, available data on microplankton communities for these river systems was not adequate to examine this question. Trends in nitrogen, phosphorus, carbon and silica indicate the Pamunkey River has the potential to be more productive than the Mattaponi River. High suspended sediment (>100 mg/L) may act to increase mortality of shad larvae (Auld and Schubel 1978). While suspended sediment typically does not exceed this threshold in the Mattaponi and Pamunkey Rivers, trends of higher turbidity exist for the Pamunkey River and may contribute to differential survival. Averages of dissolved

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oxygen and pH from March-May 1997-1999 were similar between both rivers and thus not considered to be causes of differential survival (Table 4.1).

River Morphology and Land Use

Overall sinuosity is higher in the Pamunkey River than the Mattaponi River (2.34, 1.65, respectively) (Table 4.1). Based on prior studies that demonstrate increase in habitat heterogeneity with sinuosity (Heede and Rinne 1990, Decamps 1993), the expectation would be a higher JAI in the Pamunkey River than the Mattaponi River. Since the average JAI is higher on the Mattaponi River, sinuosity is not expected to be a determinant of juvenile survival. Likewise, similarities between average depths and widths between rivers indicate morphology is an unlikely contributor to differential juvenile survival. Land use percentages are similar between these systems with forest and agriculture as dominant features, suggesting land use is not a determinant of JAI differences (Table 4.1).

Biotic differences

Predation may be a significant controlling factor in population success that is exceedingly difficult to measure. It is possible that the Pamunkey River contains larger predator populations than the Mattaponi River. Potentially important predators in these freshwater systems include striped bass (*Morone saxatilis)*, American eels (*Anguilla rostrata*), and spottail shiner (*Notropis hudsonius*) (Johnson and Dropkin 1992; Mansueti and Kolb 1953; Walburg and Nichols 1967). The striped bass juvenile index has been consistently higher in the Pamunkey River than the Mattaponi River, which may indicate higher adult

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and juvenile populations that have the potential to prey on larval/juvenile shad (Bilkovic et al. in review). While similar species have been reported in the Mattaponi and Pamunkey rivers, their abundances differ (Dawson 1992). An analysis (1983-1987, and 1991) of juvenile fish species in the Mattaponi and Pamunkey rivers, indicated *N. hudsonius* was more dominant in the Pamunkey than the Mattaponi River. This assumes that juvenile abundance is a valid indicator of adult populations of spottail shiners. Other potential predators observed by Johnson and Dropkin (1992) such as redbreast sunfish (*Lepomis auritus*), largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dolomieu*), bluegill (*Lepomis macrochirus*), tessellated darter (*Etheostoma olmstedi*) and banded killifish (*Fundulus diaphanus*) were observed in low numbers by Dawson (1992), thus conclusions on their impact on American shad could not be drawn. However, Wagner (1997) reported higher densities (#/10^3 m^2) within freshwater tidal reaches of the Pamunkey River than in the Mattaponi River (1990-1994) for several of the most frequently occurring potential shad predators: *N. hudsonius* (62.3-102.6, 43.9-55.8), *M. saxatilis* (10.7-63.0; 1.9-40.6), *L. auritus* (18.1, 12.1), and *L. macrochirus* (12.9, 2.0, respectively). McGovern and Olney (1988) noted at least two potential invertebrate predators on striped bass (the cyclopoid copepod *Acanthocyclops vernalis* and the hydra *Craspedacusta sowerbyi*). These may be predators of American shad eggs and larvae as well. Unfortunately, data was not available on these populations for comparison between rivers.

The impact of man as a predator on these populations is currently unknown. There may be historically varying fishing pressures between the rivers, which have led to differences

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in spawning adult population sizes and subsequent juvenile production. There is also an unknown impact of hatchery activities on total potential production. Since American shad are iteroparous batch spawners in Virginia, some loss of production is expected due to mortality after handling for egg removal. Although hatcheries increase fertilization rates and decrease natural mortality of larvae during rearing, they may also reduce overall productivity by removing repeat spawners from the stock. Hatchery efforts are higher in the Pamunkey River than the Mattaponi River. Historically, the Mattaponi and Pamunkey Tribal Governments have conducted hatchery activities with an unknown production level. In 1999, the estimated number of adults taken for the Mattaponi and Pamunkey Tribal Government restoration project was 1071 and 804, respectively. In addition, a state program operated by the Virginia Department of Game and Inland Fisheries (VDGIF), with support from the Virginia Marine Resources Commission (VMRC) uses the Pamunkey River stock as a source of eggs for its restoration program in the James River. From 1997-1999, these efforts have taken 9661 adult shad annually from the Pamunkey River, returning about ¼ of the produced fry to the Pamunkey River and the remainder to the James River. However, historic differences in the JAI between the rivers were evident prior to restorative efforts by VDGIF, which began in 1994. Thus, hatchery impacts by VDGIF were not the initial cause of differing population sizes between the rivers. Unequal hatchery efforts on these rivers may have occurred since the inception of the Pamunkey Tribal Government hatchery in 1918, but historic records are not available on the productivity of the tribal government hatcheries so accurate comparisons cannot be made.

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Based on zooplankton collected in concert with shad eggs/larvae, there were no significant differences in zooplankton populations between the two rivers. There may be some error associated with these comparisons due to the size selectivity imposed by the large mesh size of the net. Abundance of juvenile stages of zooplankton could not be estimated in this analysis; thus, if one of the rivers has a preponderance of zooplankton nauplii an underestimation of abundance would occur. While no significant differences existed between the rivers, higher abundance in copepods was observed in the Mattaponi River. Since copepods may be an important food item to larval shad (Levesque and Reed 1972; Marcy 1976; Crecco and Blake 1983; Johnson and Dropkin 1997) increased food availability in the Mattaponi River may enhance survival of larval shad. Additional research on zooplankton communities in both of these rivers must be conducted in order to address this possibility.

While discharge may not be the only influence on American shad survival, it impacts the transport of larvae to nursery grounds (Ulanowicz and Polgar 1980). Larval dispersal determines feeding experiences and predator exposure, and may impact mortality of larvae. In general, egg dispersal in low flow conditions is more limited than in high discharge conditions. The resulting differences in distribution could lead to varying habitat exposures and may ultimately affect growth and survival of the larvae. Extreme high flows also acted to advect eggs and larvae from tidal freshwater nursery environments into the brackish York River. Typically, the model results indicated low and average April flow values contributed to high relative habitat experience values for a population, while extreme high flows decreased these values. This pattern is not apparent

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in correlations between April discharge and JAI; in fact, an opposite trend of increasing JAI with increasing discharge is evident (Figure 4.4). This may be in part due to the lack of significant correlation between April discharge and the JAI. May and June discharge values had the most consistent correlations with JAI and should be utilized in the hydrodynamic model for more accurate matching to JAI trends. May and June flows are on average lower than April flows. Using the Mattaponi River as an example, low and average April flows (8.7 and 20.6 m^3/s), which led to high habitat experience indices in the hydrodynamic model, are similar to average and high May (14.5 and 31.1 m^3/s) and June (8.3 and 18.0 m^3/s) flows (Table 4.2). In agreement with the model, relatively high flow years in May (below 90th percentile values), which were similar to April low and average flows, were typically associated with high juvenile indices in the Mattaponi River (1991-1999); therefore, alterations in natural flow could impact shad survival. During the years of JAI analysis (1991-1999), extreme high flow in April approximating the 90th percentile used for the hydrodynamic model did not occur and the accuracy of the model could not be tested for this regime. However, declines in JAI occurred in the Pamunkey River in extreme high flows in May (> 60m^3/s) which corresponds to the scenario that extreme high flows events decrease habitat experience index values. Additionally, higher percentages of juvenile shad with May and June hatch dates in annual juvenile surveys (when flows are similar to low-average April flows) (Aiken in prep) supports the hydrodynamic model results that low to average flows result in higher habitat experience indices than high flows.

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There may be alternative explanations to differing trends in the hydrodynamic model and JAI correlation with discharge: the hydrodynamic model may not accurately depict shad distributions, other habitat factors not addressed in this study may need to be examined, and/or correlations may not describe consistent trends. The semi-demersal egg stages of American shad are believed to remain above the substrate, buoyed by currents and tides, and move with the tides until hatching (Massmann 1952). If eggs become lodged after sinking, they would be unavailable to the tides and the hydrodynamic model could not properly depict their distributions. Also, habitat suitability values were based on presence of eggs/larvae from 1997-1999 collections. A description of habitat suitability based on egg/larval distributions over a longer time period, with the inclusion of additional parameters such as prey availability, is necessary to refine the model. Similarly, the hydrodynamic model addressed egg and larval stages, while hydrographic correlations were examined using the juvenile *Alosa* indices, thus factors not addressed by the hydrodynamic model of importance to juvenile stages (e.g., predator and prey abundance and distribution) may elicit differing trends in discharge impacts. Lastly, since spurious correlations are possible (Walters and Collie 1988), trends between discharge and the JAI need to be reassessed in the future when longer-term data-sets are available and causal relationships have been established before more definitive conclusions may be deduced.

With a better understanding of natural impacts of hydrodynamics on American shad, the potential implications of a reservoir proposal in the Mattaponi River can be addressed. If water withdrawal is significant, reductions in flow could lead to decreases in juvenile

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survival, available spawning and nursery habitat, and decreased prey availability. As noted in this study, in the Mattaponi River relatively high flows and decreased extreme events (including extreme low flows) in May and June were correlated with high JAI. Thus, care must be taken to ensure sufficient flow levels and limit reservoir-induced extreme events during this time period. There are additional potential adverse impacts of a reservoir which should be considered; such as, impingement on water intake screens by eggs and early larvae which increases mortality, and potential alteration of local hydrodynamic processes, temperature and salinity regimes which could reduce available spawning and nursery habitat.

In its current form, the hydrodynamic model only has utility as a tool for evaluating hypotheses regarding current concepts of interactions between shad propagules and their environment in space and time. It serves to illustrate the potential impacts of spatial variations in habitat suitability. It may eventually be suitable for evaluating the consequences of different spawning strategies (in space and time). Hatchery release locations can then be appraised to avoid excessive larval loss from the system and/or transport to unfavorable nursery habitats. Because the model provides a spatial and temporal framework for assessing processes affecting recruitment, it can serve to integrate future advances in understanding about shad habitat utilization.

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Table 4.1. Comparison of morphology, land use and average water quality parameters between the Mattaponi and Pamunkey rivers with attributable sources noted. Abbreviations are as follows: USGS = United States Geological Survey, MRLC = Multi-Resolution Land Use Characterization, and LPR = Litho-Physiographic Region.

	Mattaponi River	Pamunkey River	Source
River Descriptors			
Watershed size (km^2)	2274	3768	Shoreline hydrology
Average annual discharge (m^3/s)	16.7	29.2	USGS
Average depth (m)*	5.5	5.0	Topographic maps, field data
Average width (m)*	206.9	206.7	Shoreline hydrology, field data
Approximate river length (km)*	85	125	Shoreline hydrology
Sinuosity*	1.65	2.34	Shoreline hydrology
Secchi depth (m)	1.0	0.6	Dixon et al. 1997
Suspended solids, total (mg/L)	11.0	28.2	USGS-river input—fall line
Turbidity (ntu)	11.1	22.1	USGS-river input—fall line
Total nitrogen (ammonia+organic N (mg/L))	0.47	0.46	USGS-river input—fall line
Phosphorus, total - whole-water (mg/L as P)	0.06	0.07	USGS-river input—fall line
Orthophosphorus, dissolved (mg/L as P)	0.02	0.017	USGS-river input—fall line
Silica, dissolved (mg/L as SiO2)	6.5	10.2	USGS-river input—fall line
Carbon, inorganic + organic, suspended (mg/L as C)	0.68	0.82	USGS-river input—fall line
Yield of total nitrogen ((lbs/acre)/yr)	1.71	2.38	USGS-river input—fall line
Yield of total phosphorus ((lbs/acre)/yr)	0.17	0.27	USGS-river input—fall line
Yield of suspended solids ((lbs/acre)/yr)	23.0	124.4	USGS-river input—fall line
Dissolved oxygen (mg/L)	9.1	9.2	This study
pH	6.9	7.3	This study
Percentage of entire watershed			
Urban (%)	1.0	2.2	MRLC
Crop (%)	15.2	15.3	MRLC
Grass (%)	7.3	11.3	MRLC
Forest (%)	66.7	63.2	MRLC
Wetlands (%)	8.0	6.0	MRLC
Area of entire watershed (km^2)			
Water	40.7	104.9	MRLC
Urban	21.76	50.3	MRLC
Crop	346.31	576.27	MRLC
Grass	164.87	426.65	MRLC
Forest	1517.24	2380.23	MRLC
Wetlands	182.99	227.63	MRLC
% of upper watershed in Piedmont	38.7	93	Johnson and Belval, 1998
% of Coastal Plain LPR in the upper watershed	61.3	7	Johnson and Belval, 1998

* estimates based on area of river between the fall lines and the river mouths

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Table 4.2. Median, 10 and 90 percentiles of 14-day moving averages of discharge (m^3/s) in the Mattaponi and Pamunkey rivers in 1979-1998.

Mattaponi River	March	April	May	June
Minimum (10%)	11.3	8.7	4.6	2.2
Median	23.5	20.6	14.5	8.3
Maximum (90%)	60.5	68.2	31.1	18.0
Pamunkey River	March	April	May	June
Minimum (10%)	17.5	12.6	9.1	4.3
Median	44.5	33.1	25.3	12.6
Maximum (90%)	88.1	125.7	59.7	28.4

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Table 4.3. Mean, minimum (min) and maximum (max) discharge values (m^3/s) of the Mattaponi River, and the American shad juvenile annual index (JAI) for 1991-1999. Discharge data was obtained from USGS stream gauge stations located at the fall line of the Mattaponi River (Beulahville station (#01674500)).

	March			April			May			June			
Year	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	JAI
1991	15.6	8.1	33.7	17.1	8.0	51.0	5.3	1.8	7.9	1.3	0.7	2.1	93.5
1992	20.1	8.9	33.4	11.3	6.7	39.9	7.5	3.7	13.6	6.5	1.9	15.9	37.3
1993	61.7	20.1	134.2	54.4	29.2	24.8	29.1	11.8	53.0	10.2	3.9	20.3	973.4
1994	68.1	25.8	160.6	51.5	15.6	78.4	18.0	6.5	44.2	5.1	3.1	6.6	1055.0
1995	17.3	7.1	56.4	8.2	4.6	220.3	10.7	3.9	22.4	9.6	1.4	35.4	273.2
1996	23.6	17.8	38.2	33.3	13.2	17.6	17.9	9.0	29.2	12.1	6.4	24.1	6325.1
1997	35.2	24.6	55.8	22.0	16.4	68.5	15.0	6.8	40.8	11.6	3.3	32.6	2103.4
1998	69.1	37.1	36.2	44.3	20.7	127.1	30.2	11.9	63.4	12.3	6.5	20.2	2544.2
1999	22.4	8.4	47.0	8.8	4.7	12.4	2.6	1.1	4.5	0.6	0.4	1.0	298.0

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Table 4.4. Mean, minimum (min) and maximum (max) discharge values (m^3/s) of the Pamunkey River, and the American shad juvenile annual index (JAI) for 1991- 1999. Discharge data was obtained from USGS stream gauge stations located at the fall line of the Pamunkey River (Hanover station (#01673000)).

	March			April			May			June			
Year	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	JAI
1991	23.6	11.8	132.2	22.8	13.7	138.5	41.6	3.2	14.0	4.0	2.0	12.3	129
1992	63.5	17.5	76.7	35.6	9.0	73.1	74.6	7.8	45.9	17.8	5.3	68.5	1.9
1993	35.7	27.8	373.8	55.8	39.6	235.9	65.2	17.6	150.6	14.6	5.7	35.1	12.0
1994	31.6	37.7	577.7	26.6	23.4	461.6	7.5	14.2	96.0	10.1	6.7	13.3	571.0
1995	37.1	12.7	237.3	20.5	7.2	28.6	17.0	5.6	55.2	31.5	2.9	261.9	88.6
1996	139.5	22.7	142.7	98.4	21.5	157.7	43.7	16.4	60.9	21.3	8.4	65.7	1082.5
1997	68.7	35.4	165.1	36.4	21.7	117.2	20.6	9.7	55.5	12.8	4.3	45.9	169.2
1998	137.9	45.3	390.8	80.1	30.9	188.3	59.7	20.8	203.3	18.0	8.7	30.6	89.2
1999	41.4	13.6	173.0	13.9	8.3	20.1	5.6	4.0	8.1	2.3	1.8	3.9	79.8

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Table 4.5. Results of Pearson correlation between mean, minimum, maximum discharge (m^3/s) and American shad juvenile Index (JAI) for the Mattaponi and Pamunkey rivers (1991-1999). Values in bold are significant correlations ($p<0.05$).

	Mattaponi River (JAI)		**Pamunkey River (JAI)**	
Discharge (m^3/s)	Correlation Coefficient	P-value	Correlation Coefficient	P-value
Mean				
March	0.51	0.16	0.26	0.50
April	0.61	0.08	0.23	0.55
May	**0.80**	**0.01**	**-0.70**	**0.05**
June	**0.67**	**0.05**	-0.06	0.89
Minimum				
March	**0.72**	**0.03**	0.24	0.54
April	0.58	0.09	0.08	0.85
May	**0.81**	**0.01**	0.16	0.68
June	**0.82**	**0.01**	0.20	0.60
Maximum				
March	0.22	0.57	0.27	0.48
April	-0.02	0.96	0.35	0.36
May	**0.69**	**0.04**	-0.06	0.87
June	0.41	0.27	-0.06	0.87

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Table 4.6. Regression equations, p-values and adjusted r-squared percentages of the natural logarithm of the index of abundance of American shad for the Mattaponi River (y_m) and Pamunkey River (y_p) and the respective monthly discharge average, minimum and maximum. The independent variable discharge (X) is denoted with a subset of the month and type of discharge: average = ave, minimum = min and maximum = max. Bold values indicate statistical significance ($p < 0.05$).

Mattaponi River			Pamunkey River		
Regression Equation	**p-value**	**R^2**	**Regression Equation**	**p-value**	**R^2**
$y_m = 5.05 + 0.037 (X_{Marchave})$	0.21	11.9	$y_p = 3.65 + 0.012 (X_{Marchave})$	0.53	0
$y_m = 4.72 + 0.059 (X_{Aprilave})$	0.11	26.0	$y_p = 3.60 + 0.018 (X_{Aprilave})$	0.56	0
$y_m = 3.90 + 0.143 (X_{Mayave})$	**0.01**	**63.9**	$y_p = 6.85 - 0.059 (X_{Mayave})$	**0.05**	**41.3**
$y_m = 3.72 + 0.321 (X_{Juneave})$	**0.04**	**43.5**	$y_p = 4.71 - 0.017 (X_{Juneave})$	0.87	0
$y_m = 4.24 + 0.012 (X_{Marchmin})$	**0.04**	**43.6**	$y_p = 3.35 + 0.041 (X_{Marchmin})$	0.55	0
$y_m = 4.69 + 0.13 (X_{Aprilmin})$	0.13	22.6	$y_p = 4.12 + 0.015 (X_{Aprilmin})$	0.85	0
$y_m = 4.31 + 0.27 (X_{Maymin})$	**0.01**	**64.1**	$y_p = 3.77 + 0.056 (X_{Maymin})$	0.69	0
$y_m = 4.15 + 0.69 (X_{Junemin})$	**0.01**	**66.0**	$y_p = 3.37 + 0.192 (X_{Junemin})$	0.59	0
$y_m = 6.01 + 0.007 (X_{Marchmax})$	0.64	0	$y_p = 3.57 + 0.003 (X_{Marchmax})$	0.51	0
$y_m = 6.64 - 0.002 (X_{Aprilmax})$	0.85	0	$y_p = 3.42 + 0.006 (X_{Aprilmax})$	0.36	0
$y_m = 4.28 + 0.064 (X_{Maymax})$	**0.05**	**42.0**	$y_p = 4.63 - 0.002 (X_{Maymax})$	0.86	0
$y_m = 5.40 + 0.055 (X_{Junemax})$	0.38	0	$y_p = 4.54 - 0.002 (X_{Junemax})$	0.87	0

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Table 4.7. Average monthly water temperature and total monthly precipitation in the York River Watershed for March through June, 1991-1999. Precipitation data for the state of Virginia was obtained from National Climatic Data Center, and water temperature was obtained from the VIMS Ferry Pier Ambient Monitoring Data located at the mouth of the York River in Gloucester Point.

	Water Temperature				Total Precipitation			
Year	**March**	**April**	**May**	**June**	**March**	**April**	**May**	**June**
1991	9.5	14.5	21.1	25.5	5.9	0.9	0.9	6.2
1992	7.8	13.0	17.7	22.3	5.9	2.2	5.0	2.3
1993	6.0	12.0	19.0	23.7	7.2	3.2	4.7	1.8
1994	7.7	14.7	18.0	24.6	7.9	2.7	2.5	1.7
1995	9.0	14.0	18.8	24.1	3.0	2.0	4.3	1.9
1996	6.6	11.9	18.7	25.8	2.7	2.9	3.2	4.4
1997	10.1	12.9	17.2	22.3	3.0	3.9	1.4	2.2
1998	9.5	15.0	19.2	24.2	6.7	4.3	3.4	4.4
1999	9.3	15.3	18.7	24.1	4.0	2.6	2.8	6.3

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Table 4.8. Results of Pearson correlation between total precipitation (cm) and water temperature (°C) and American shad juvenile Index (JAI) for the Mattaponi and Pamunkey rivers (1991-1999). Values in bold are significant ($p < 0.05$).

	Mattaponi River (JAI)		Pamunkey River (JAI)	
Total Precipitation	Correlation Coefficient	P-value	Correlation Coefficient	P-value
March	-0.17	0.66	-0.29	0.45
April	**0.73**	**0.03**	0.09	0.82
May	-0.16	0.68	-0.61	0.08
June	-0.10	0.80	0.24	0.54
Water Temperature				
March	-0.19	0.63	0.13	0.75
April	-0.27	0.49	0.16	0.69
May	-0.22	0.58	0.11	0.78
June	0.28	0.48	**0.67**	**0.05**

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Table 4.9. Correlations between discharge (m^3/s), water temperature (°C), and precipitation (cm). Results of Pearson correlation are indicated with correlation coefficients and p-values. Significant relationships ($p < 0.05$) are in bold. Precipitation data for the state of Virginia was obtained from National Climatic Data Center, and water temperature was obtained from the VIMS Ferry Pier Ambient Monitoring Data located at the mouth of the York River in Gloucester Point.

	March		April		May		June	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
DISCHARGE				**PRECIPITATION**				
Pamunkey River								
March	-0.24	0.53	0.59	0.09	0.11	0.77	0.15	0.70
April	-0.04	0.91	0.53	0.14	0.21	0.59	0.01	0.98
May	0.34	0.37	0.11	0.79	0.49	0.18	-0.10	0.80
June	-0.28	0.47	-0.23	0.56	0.60	0.09	-0.52	0.15
Mattaponi River								
March	**0.70**	**0.04**	0.07	0.06	0.10	0.79	-0.36	0.34
April	0.64	0.06	0.51	0.16	0.08	0.83	-0.33	0.39
May	0.22	0.58	**0.67**	**0.05**	0.26	0.50	-0.30	0.44
June	-0.21	0.59	**0.69**	**0.04**	0.33	0.39	-0.52	0.15
DISCHARGE				**TEMPERATURE**				
Pamunkey River								
March	-0.24	0.53	-0.09	0.81	-0.16	0.68	-0.05	0.89
April	-0.53	0.14	-0.20	0.60	-0.02	0.96	0.20	0.60
May	-0.52	0.15	-0.45	0.22	-0.07	0.86	-0.20	0.61
June	-0.23	0.55	-0.58	0.11	-0.37	0.33	-0.19	0.63
Mattaponi River								
March	-0.07	0.85	-0.23	0.56	-0.13	0.72	-0.16	0.69
April	-0.44	0.23	-0.50	0.17	-0.00	0.99	0.29	0.45
May	-0.41	0.28	-0.48	0.20	-0.16	0.68	-0.18	0.64
June	-0.18	0.64	-0.33	0.38	-0.22	0.58	-0.09	0.82
PRECIPITATION				**TEMPERATURE**				
Mattaponi and Pamunkey Rivers								
March	-0.29	0.46	0.24	0.53	0.20	0.61	0.00	0.99
April	0.00	0.99	-0.15	0.69	-0.53	0.14	-0.37	0.33
May	-0.57	0.11	-0.33	0.38	-0.27	0.49	-0.30	0.43
June	0.37	0.33	0.46	0.22	0.64	0.07	0.53	0.15

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Table 4.10. Correlation between number of days within historical 25% and 75% quartiles of average daily flow and the American shad juvenile index (JAI) in the Mattaponi and Pamunkey rivers. Values in bold are significant ($p < 0.05$).

	Mattaponi River (JAI)		**Pamunkey River (JAI)**	
	Correlation Coefficient	P-value	Correlation Coefficient	P-value
March	0.19	0.65	0.22	0.56
April	0.50	0.18	0.51	0.17
May	**0.79**	**0.01**	0.34	0.37
June	**0.81**	**0.001**	0.32	0.41

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Table 4.11. Number of days within historical 25% and 75% quartiles of average daily flow for the Mattaponi and Pamunkey rivers. Discharge data was obtained from USGS stream gauge stations located at the approximate fall lines of the Pamunkey and Mattaponi rivers (Hanover station (#01673000); Beulahville station (#01674500), respectively).

	Pamunkey River				Mattaponi River			
Year	**March**	**April**	**May**	**June**	**March**	**April**	**May**	**June**
1991	3	9	0	1	7	9	0	0
1992	11	4	11	14	15	6	8	8
1993	2	10	23	5	2	3	19	14
1994	13	21	25	14	9	15	14	15
1995	1	3	19	13	3	3	16	11
1996	5	19	27	19	20	17	28	20
1997	20	25	22	2	20	28	21	17
1998	14	11	21	15	1	6	16	20
1999	4	0	0	15	6	0	0	0

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Table 4.12. Index values derived for population habitat experience under two different sets of habitat suitability values. For both scenarios spawning is assumed to be spread evenly among the three potential release sites on each river, and time of egg hatching is set at tidal cycle 20 (of 30). In scenario 1, habitat suitability is assumed to be equal and moderate in all river sections. In scenario 2, habitat suitability is assumed to be higher in upper and middle river sections for eggs, and higher in middle and lower river sections for larvae.

Index values for population habitat experience			
	High flow	Medium flow	Low flow
Mattaponi River			
Scenario 1	52	62	62
Scenario 2	58	81	85
Pamunkey River			
Scenario 1	49	59	60
Scenario 2	56	83	87

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Table 4.13. Index values derived for population habitat experience under three different spawning release sites. For all scenarios habitat suitability is assumed to be higher in upper and middle river sections for eggs, and higher in middle and lower river sections for larvae, and time of egg hatching is set at tidal cycle 20 (of 30). In scenario 1, spawning is assumed to primarily occur in upper and mid river sections. In scenario 2, spawning is assumed to be spread evenly among the three potential release sites on each river. In scenario 3, spawning is assumed to primarily occur in mid and lower river sections.

Index values for population habitat experience			
	High flow	Medium flow	Low flow
Mattaponi River			
Scenario 1	70	88	95
Scenario 2	65	80	84
Scenario 3	61	73	76
Pamunkey River			
Scenario 1	60	88	92
Scenario 2	55	82	96
Scenario 3	51	78	82

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Figure 4.1. Map depicting release locations of eggs in upstream, mid-river, and downstream reaches used in hydrodynamic model simulations of the Mattaponi and Pamunkey rivers.

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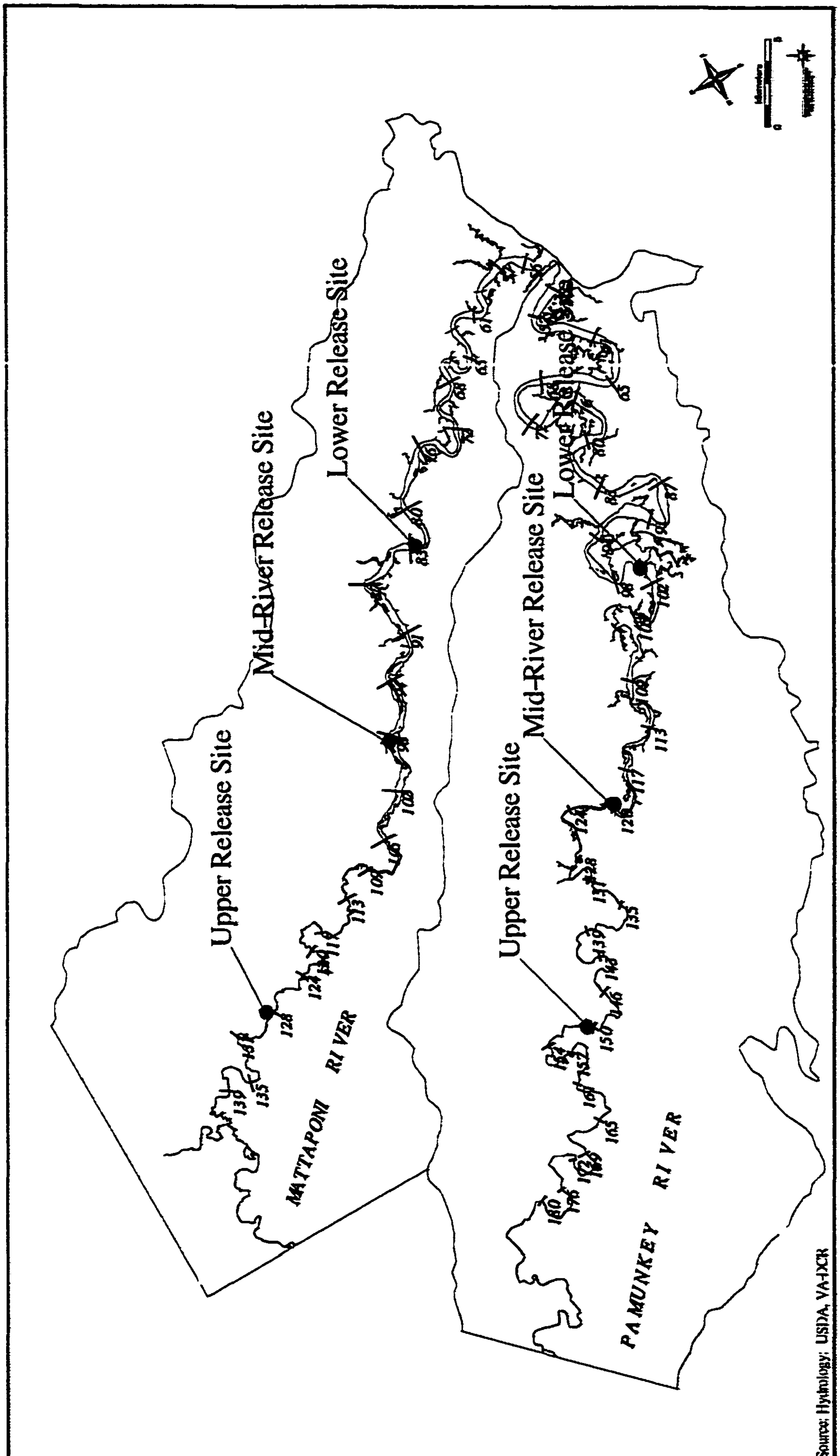

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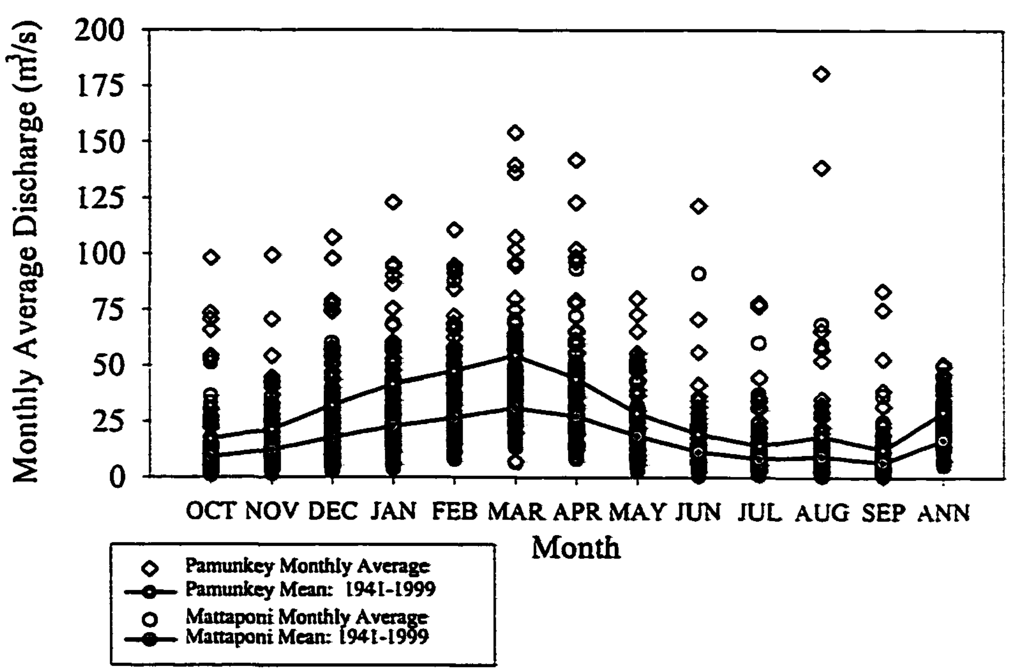

Figure 4.2. Average monthly discharge (m³/s) for the Mattaponi and Pamunkey rivers from 1941-1999, with the overall trend of long-term monthly averages superimposed.

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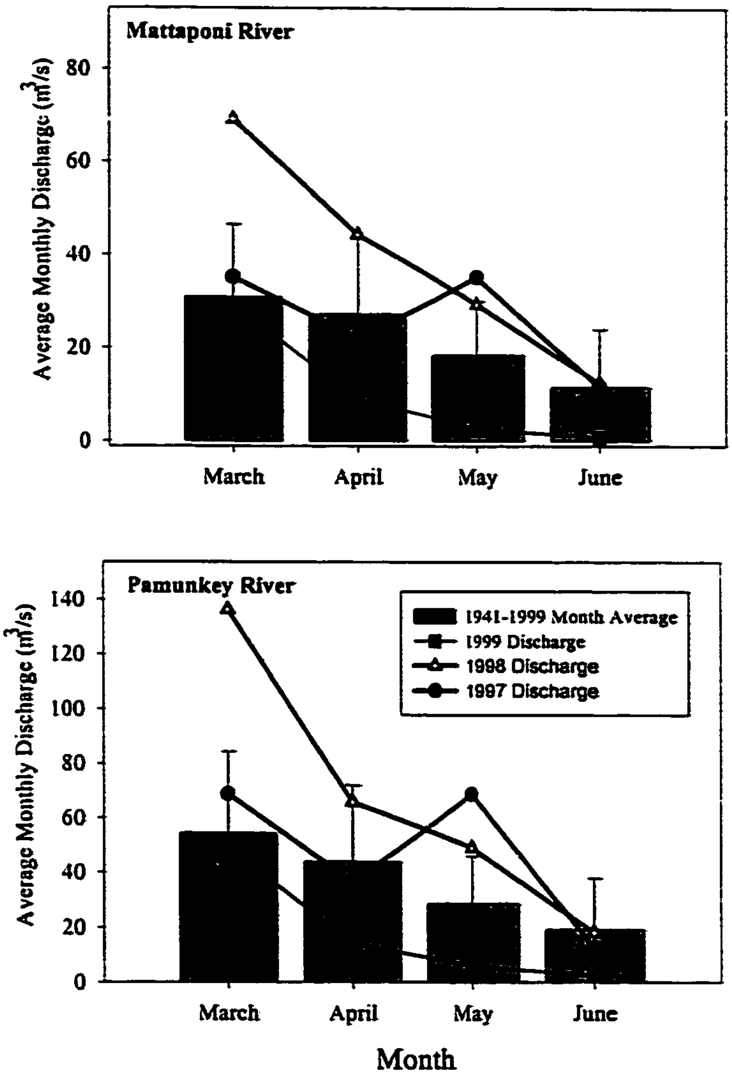

Figure 4.3. Average monthly discharge data (1941-1999) with standard errors. Trends in average monthly discharge during ichthyoplankton sampling (1997-1999) are denoted separately.

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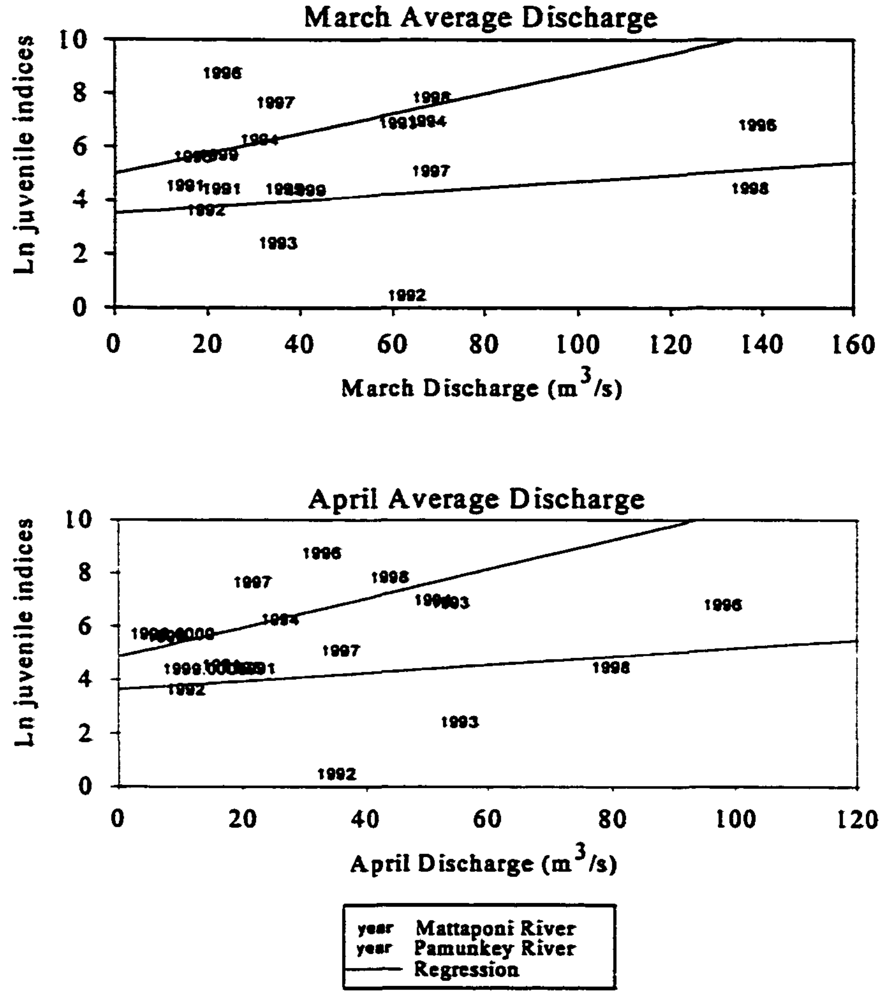

Figure 4.4. Regressions of the natural logarithm of the annual index of abundance of American shad (1991-1999) for the Mattaponi River (blue) and the Pamunkey River (red) and the respective monthly average discharge for the months of March, April, May and June.

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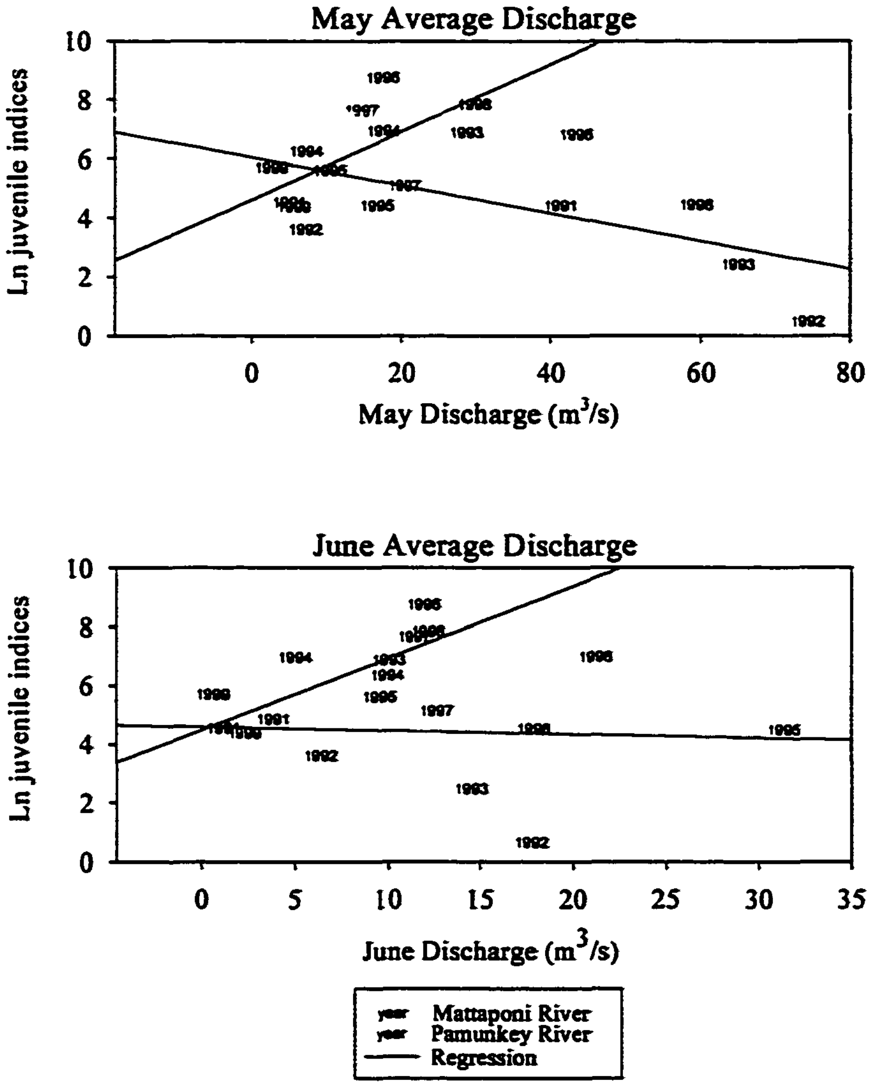

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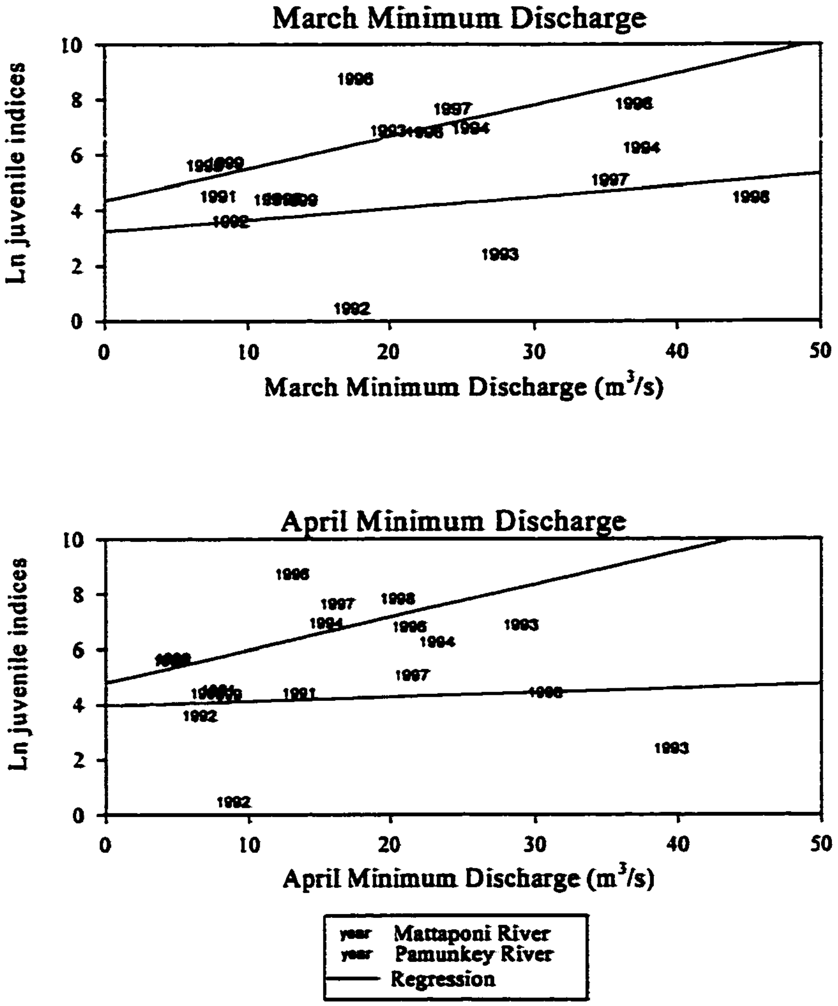

Figure 4.5. Regressions of the natural logarithm of the annual index of abundance of American shad (1991-1999) for the Mattaponi River (blue) and the Pamunkey River (red) and the respective monthly minimum discharge for the months of March, April, May and June.

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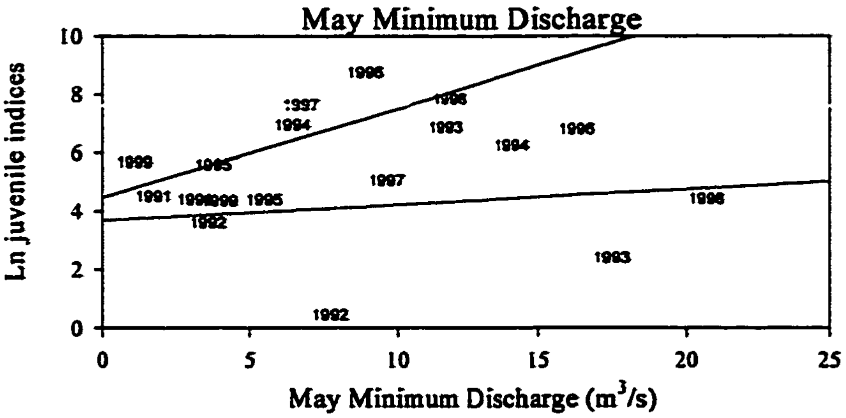

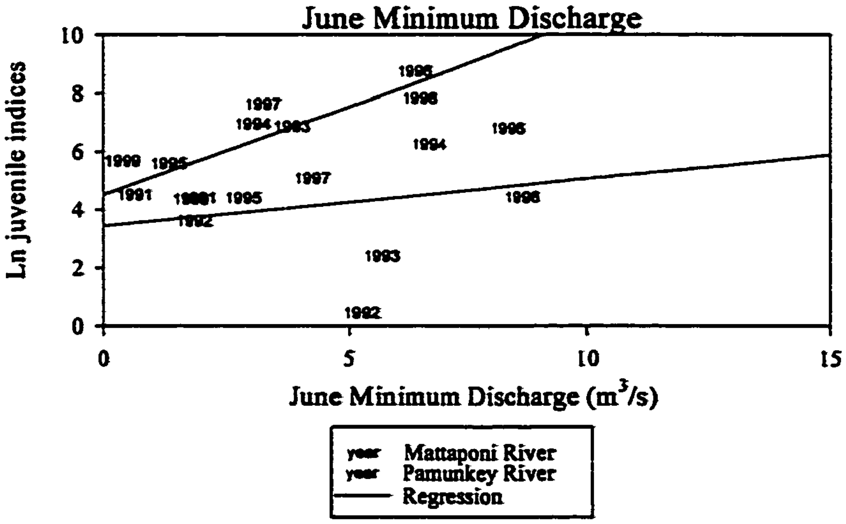

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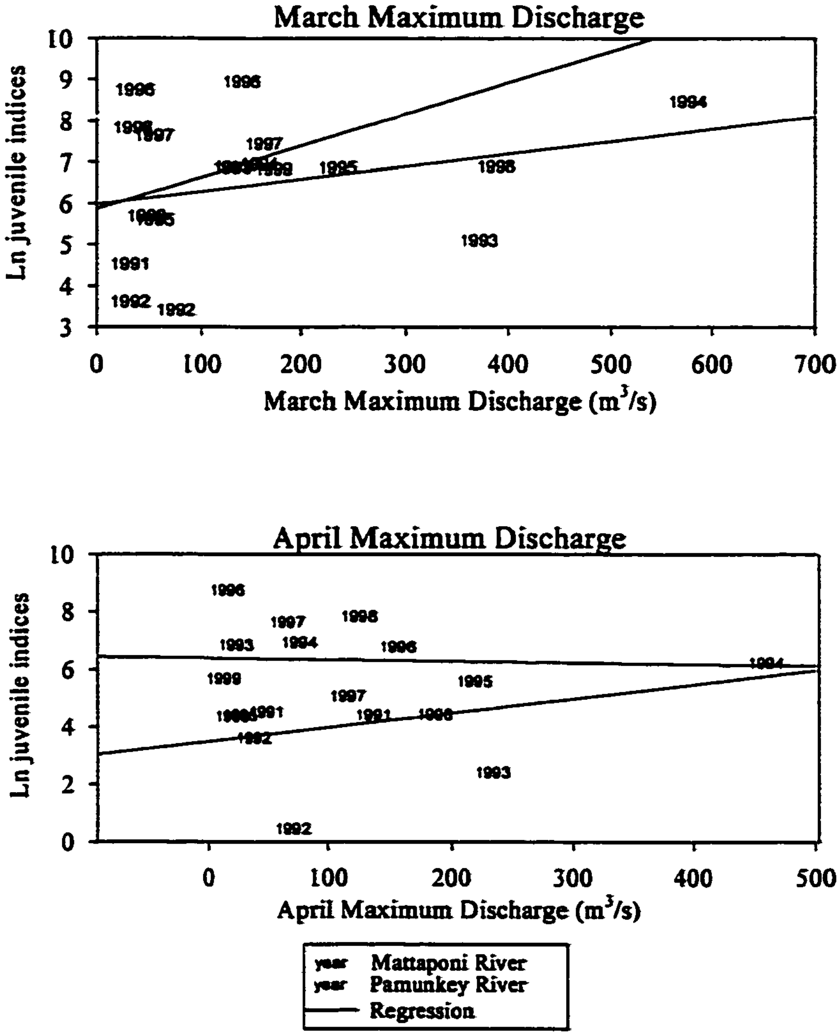

Figure 4.6. Regressions of the natural logarithm of the annual index of abundance of American shad (1991-1999) for the Mattaponi River (blue) and the Pamunkey River (red) and the respective monthly maximum discharge for the months of March, April, May and June.

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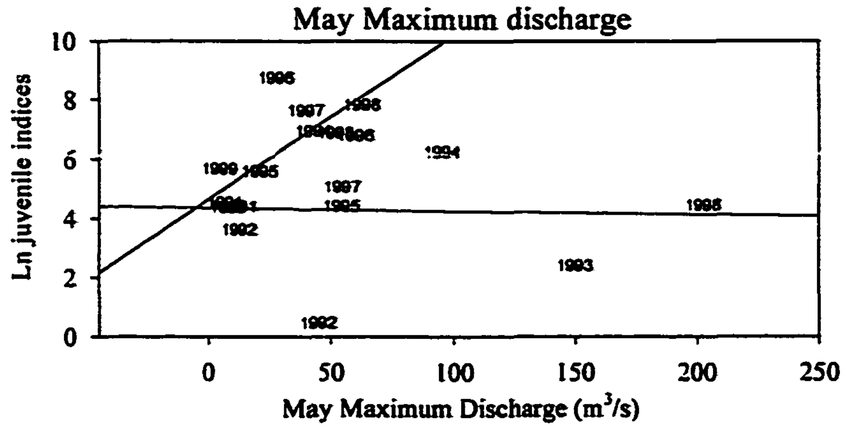

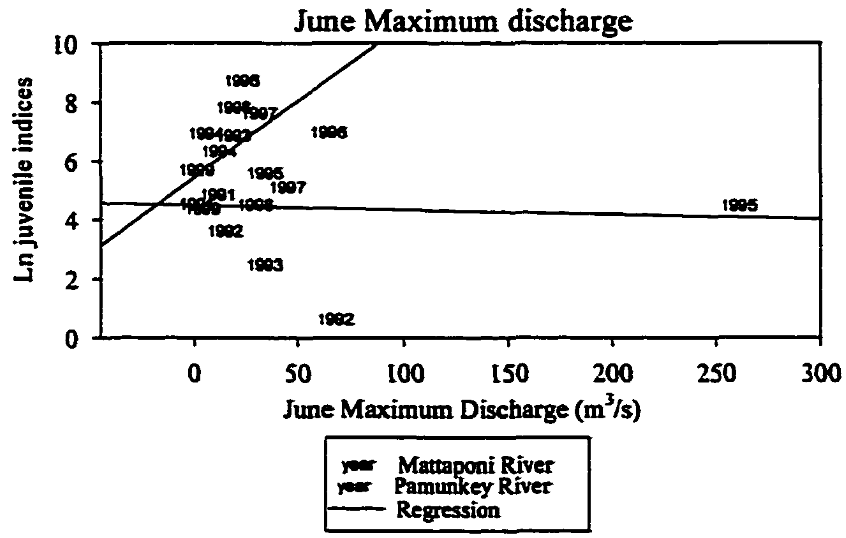

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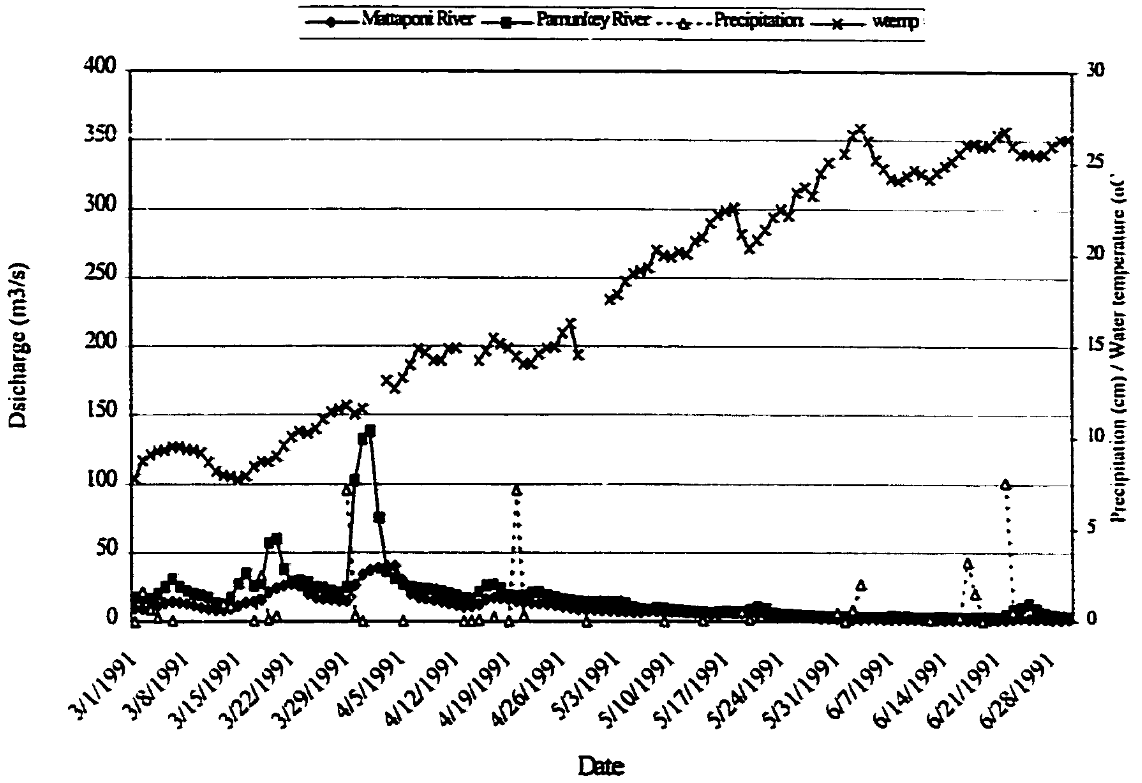

Figure 4.7. Daily spring discharge (m^3/s), precipitation (cm) and water temperature (°C) in the Mattaponi and Pamunkey rivers, 1991.

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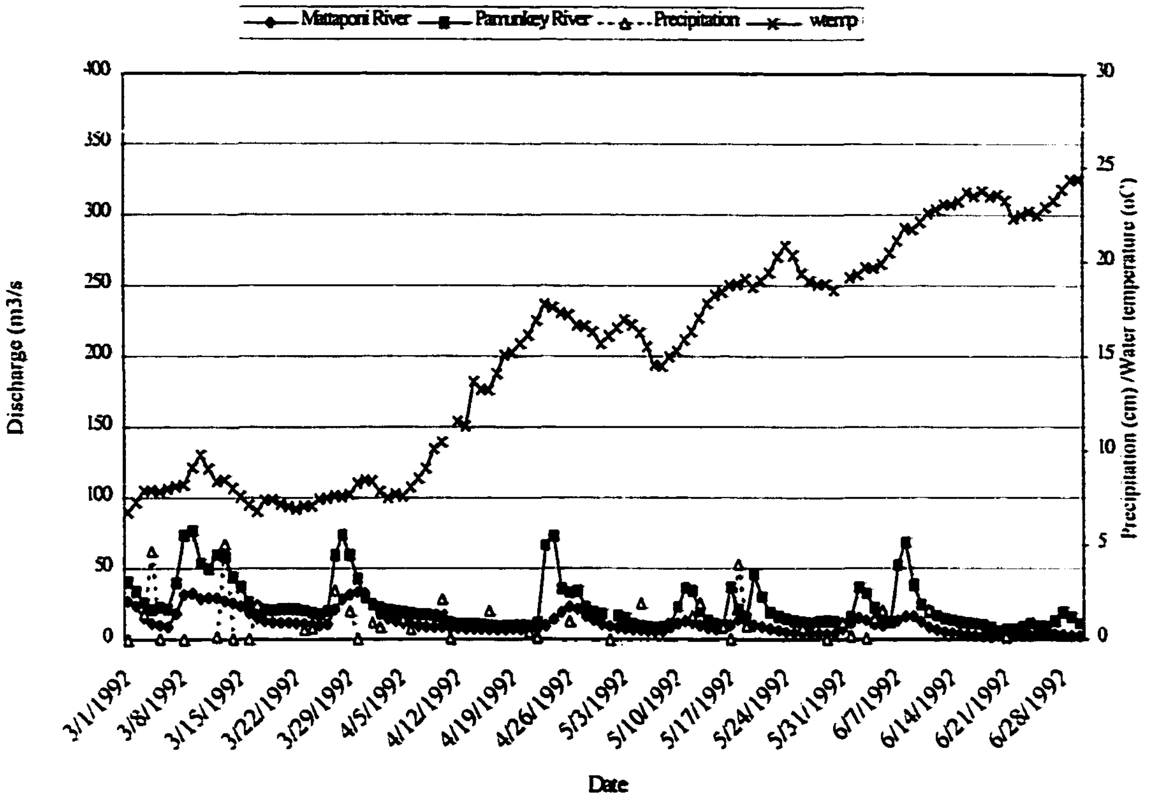

Figure 4.8. Daily spring discharge (m^3/s), precipitation (cm) and water temperature (°C) in the Mattaponi and Pamunkey rivers, 1992.

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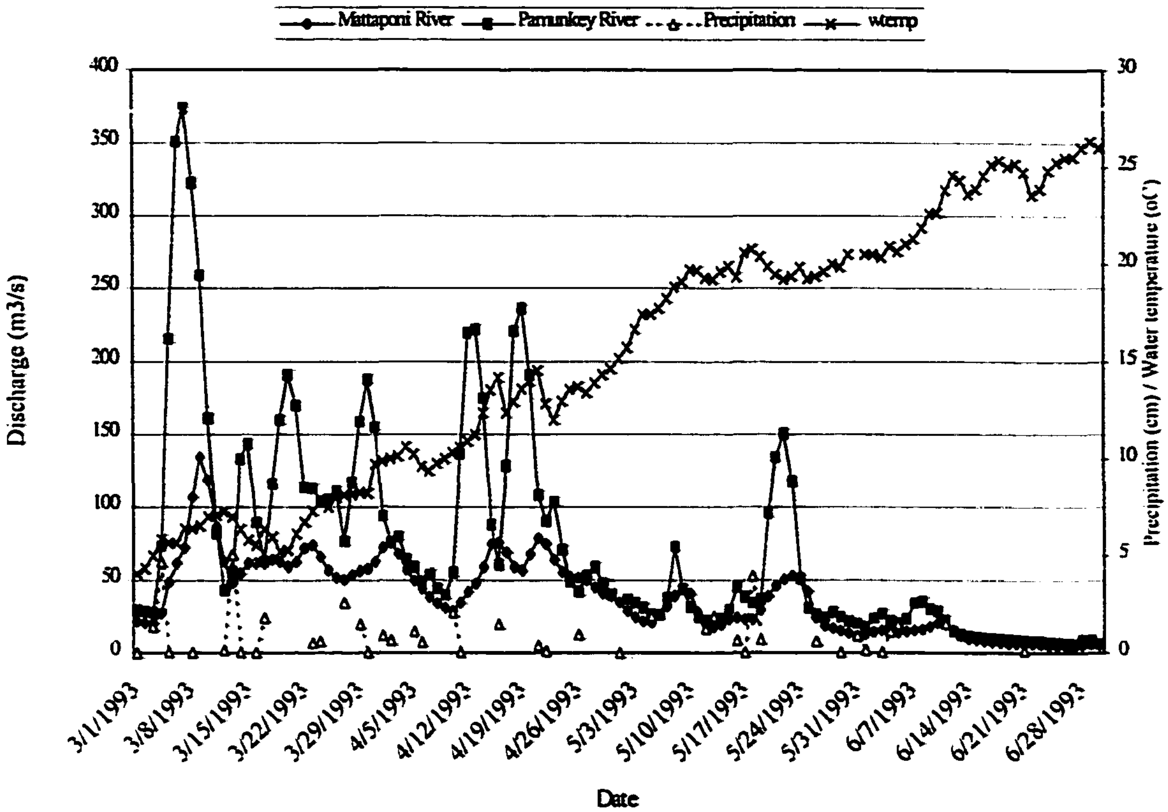

Figure 4.9. Daily spring discharge (m³/s), precipitation (cm) and water temperature (°C) in the Mattaponi and Pamunkey rivers, 1993.

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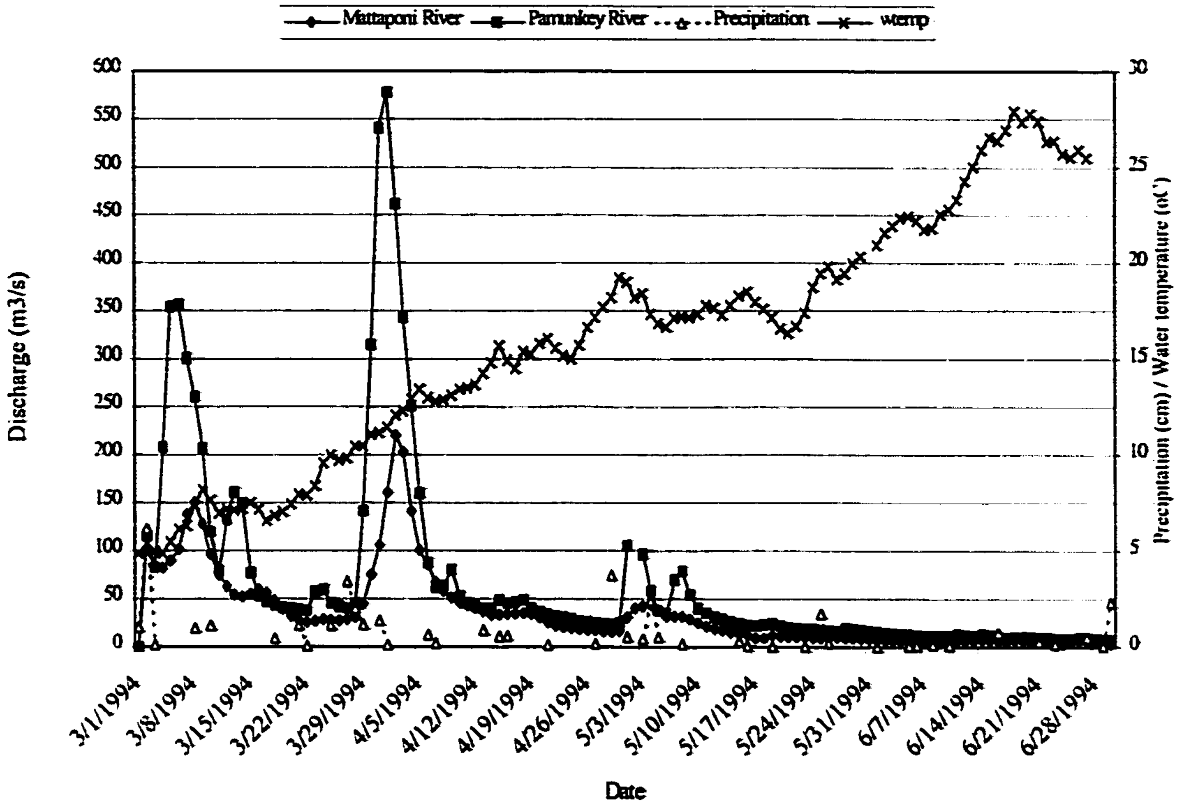

Figure 4.10. Daily spring discharge (m^3/s), precipitation (cm) and water temperature(• C) in the Mattaponi and Pamunkey rivers, 1994.

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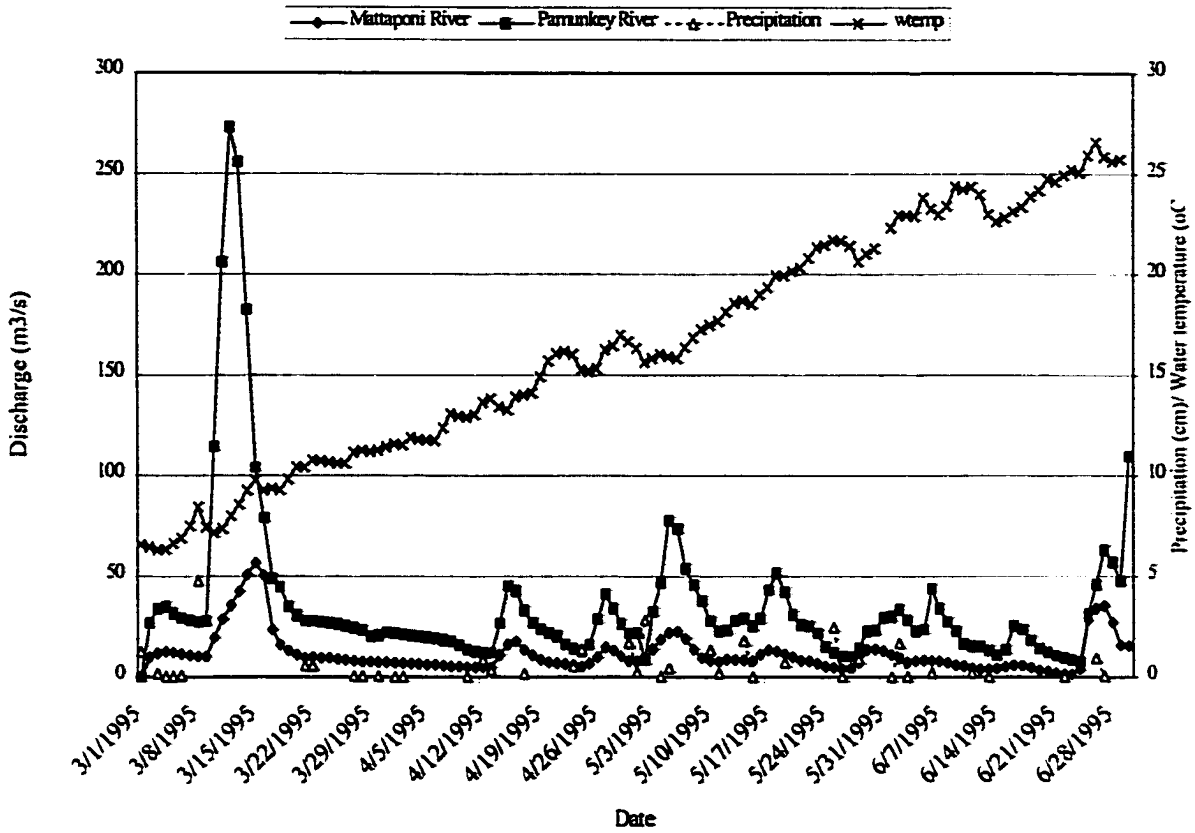

Figure 4.11. Daily spring discharge (m^3/s), precipitation (cm) and water temperature(°C) in the Mattaponi and Pamunkey rivers, 1995.

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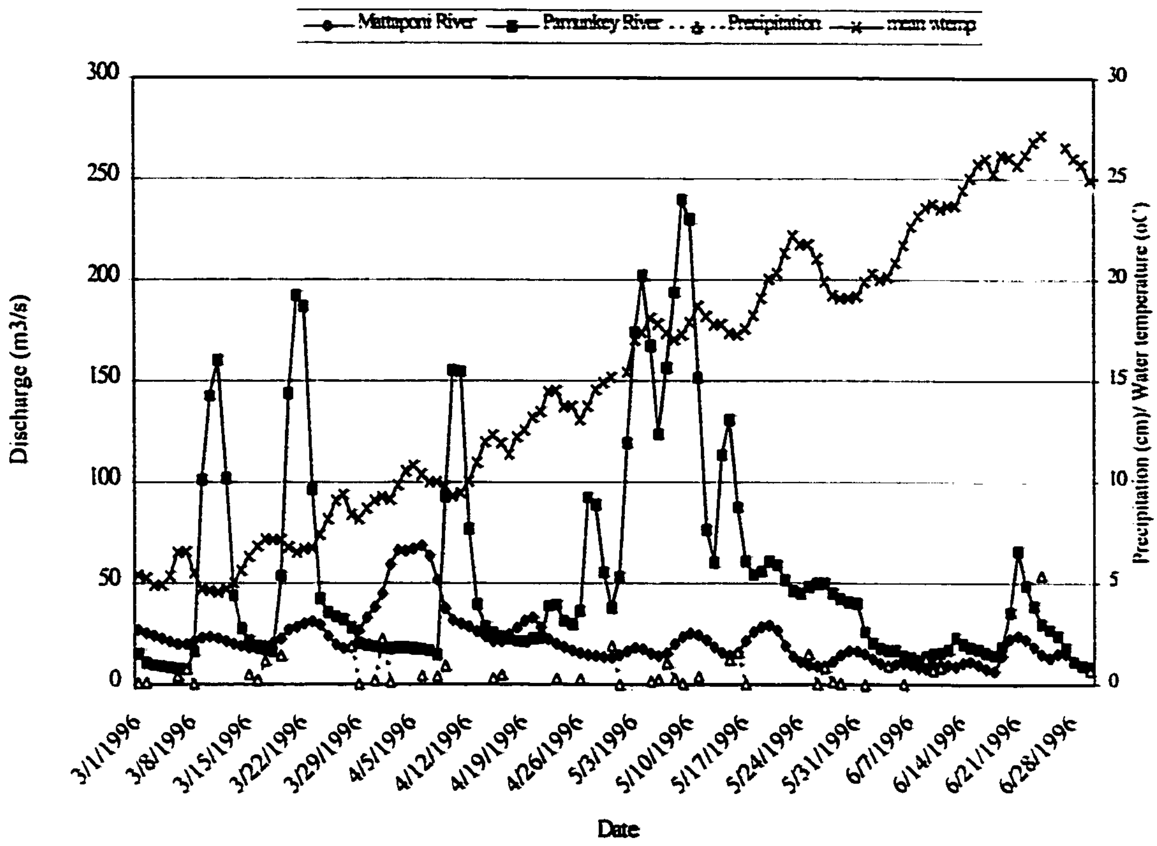

Figure 4.12. Daily spring discharge (m^3/s), precipitation (cm) and water temperature($\circ$C) in the Mattaponi and Pamunkey rivers, 1996.

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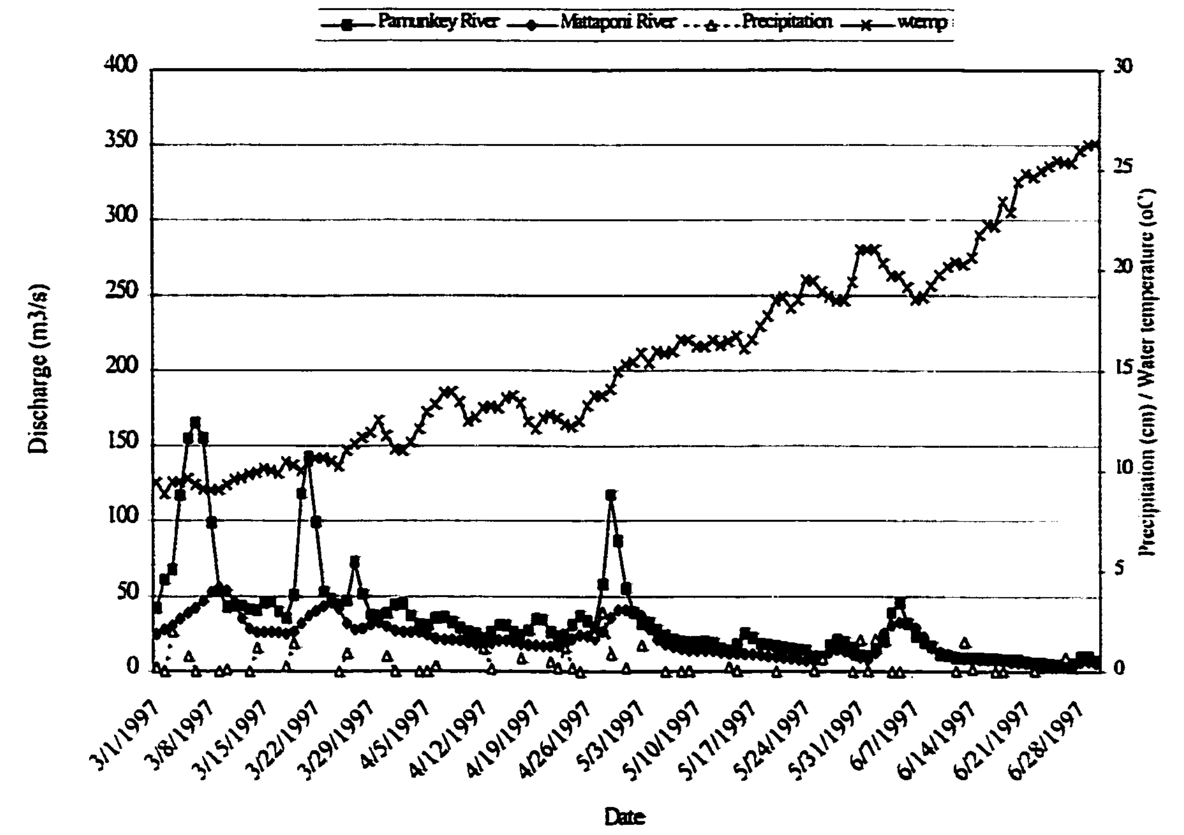

Figure 4.13. Daily spring discharge (m^3/s), precipitation (cm) and water temperature(°C) in the Mattaponi and Pamunkey rivers, 1997.

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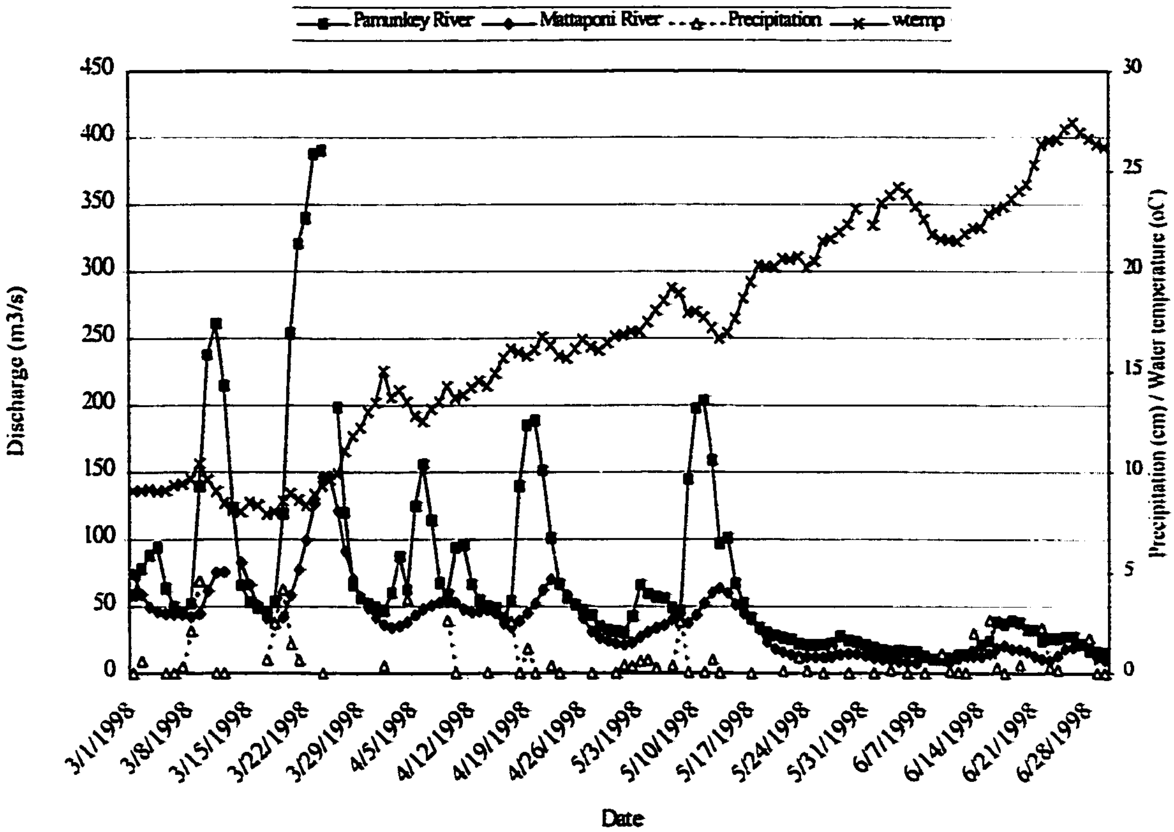

Figure 4.14. Daily spring discharge (m^3/s), precipitation (cm) and water temperature(• C) in the Mattaponi and Pamunkey rivers, 1998.

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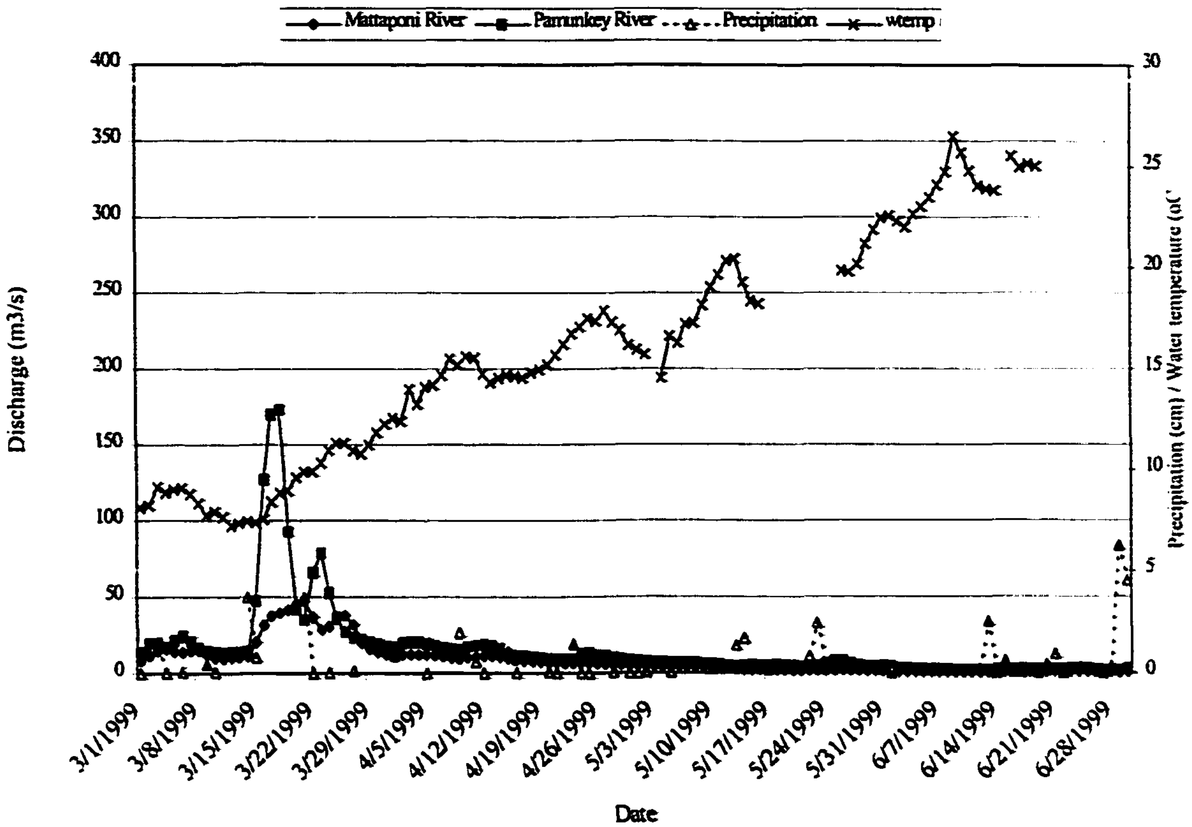

Figure 4.15. Daily spring discharge (m^3/s), precipitation (cm) and water temperature(• C) in the Mattaponi and Pamunkey rivers, 1999.

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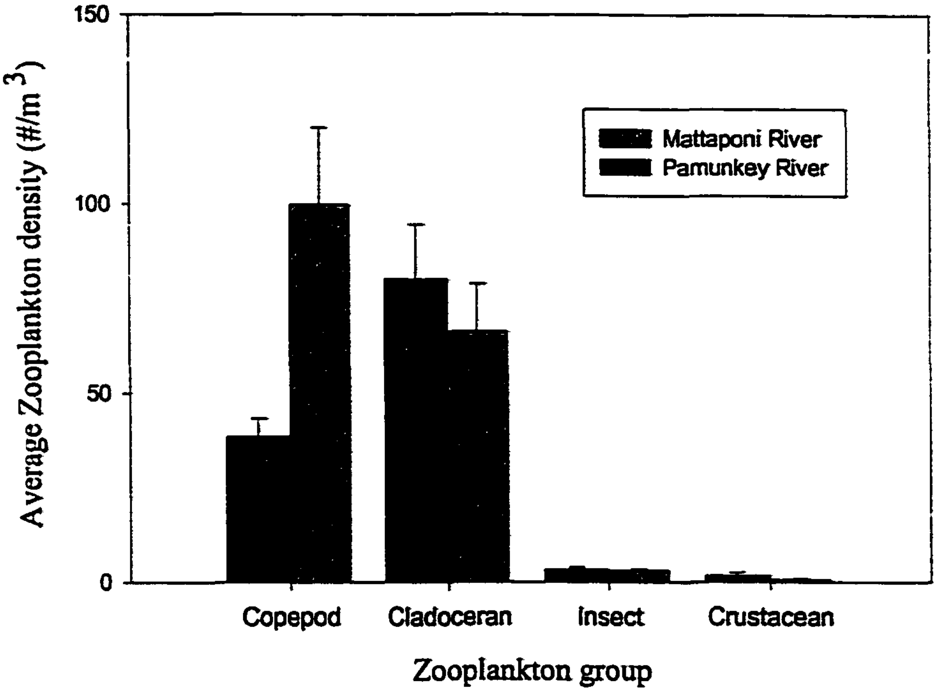

Figure 4.16. Average zooplankton density with standard error within tidal freshwater sampled areas during ichthyoplantkon collections in the Mattaponi and Pamunkey rivers (1997-1999).

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Summary

Essential fish habitat (EFH) is defined as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (Magnuson-Stevens Act, 16 U.S.C. 1801 et esq). With new mandates to identify and protect EFH for all species managed under Fisheries Management Plans (FMPs), evaluation of fish habitat has become a priority. So how does one describe EFH under the broad definition listed above? Cost and data limitations often preclude extensive habitat evaluations, especially for migratory species that utilize large expanses of habitat during their life history or species with complex stock structures. Further, identifying the 'essential' components of such habitats is problematic, especially in species for which there is only a partial knowledge of life history. In the case of American shad, much of what is known about natural spawning and early life history is either anecdotal or incompletely described for all stocks.

The main objective of this study was the development and evaluation of watershed habitat assessment tools for the early life stages of American shad (Alosa sapidissima), an anadromous fish managed with a FMP, in two coastal plain rivers of Virginia. Efforts are underway to restore populations that have experienced drastic declines, and information on habitat suitability and EFH may enhance management efforts. In order to begin the main objective, it was necessary to delineate current American shad spawning and nursery habitat reaches in the Mattaponi and Pamunkey Rivers. This was accomplished using egg and larval presence/absence data obtained during ichthyoplankton collections

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(1997-1999). Two important observations resulted from collections: spawning locations were primarily located in upstream and mid-river reaches with larvae dispersed throughout the sampled areas; and American shad eggs and larvae were more abundant on the Mattaponi than Pamunkey by a factor of 5.5 and 4.6, respectively.

To combine ichthyoplankton data with habitat evaluation, habitat suitability index (HSI) models were first postulated based on extensive literature reviews of hydrographic, physical habitat, shoreline and land use features that are potential influences on American shad production in the Mattaponi and Pamunkey rivers. Deficiencies in available data for shad included land use and physical habitat parameters, and in these cases HSI models were hypothesized based on scientific literature of similar systems or species. HSI models in conjunction with values of habitat parameters were then used to rate habitat. This macroscale (m-km) habitat assessment protocol separately rated habitat in the rivers based on hydrographic, physical habitat, shoreline and land use parameters. Values for parameters used in the ratings were obtained from a variety of sources in attempts to combine best-available data. These sources consisted of a combination of field assessments (1997-1999), long-term data sets (water quality) and remote sensing (land use). To corroborate habitat ratings and HSI models, the parameters included in habitat ratings were examined for associations with presence of egg and larvae (1997-1999).

Rated habitat based solely on hydrographic parameters indicated that the entire tidal freshwater segments of the rivers were optimal for shad egg and larval stages. However,

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there is evidence of spawning selection of upstream and mid-river reaches based on the absence of eggs in downstream reaches. Principal components analyses and logistic regressions indicate the importance of hydrographic parameters (current velocity, dissolved oxygen and depth); physical habitat features (sediment type and deadfall) forested shoreline, and land use features to presence of eggs which are features of upstream and mid-river habitats. The use of physical habitat, shoreline/land use ratings more closely corresponded to observed distributions of eggs within the rivers. Larvae were more dispersed than eggs and distinct habitat associations could not be discerned, thus ratings were not accurate for larval distributions. This corresponds to the hypothesis that (more so than eggs) are subjected to net downstream transport. Since habitat ratings did not completely coincide with field collections (e.g., shad eggs were present in low rated habitat at times), additional parameters may need to be examined, and/or habitat suitability index models refined. This study presents a watershed approach since it includes physical habitat, land use and riparian features in habitat assessment. The combination of remote sensing and on-site data collection and analyses used here may be an effective way to rapidly assess habitat suitability when data are limited. It allows for the linkage of fish population data with habitat evaluations. As more data becomes available and HSI models are refined, habitat ratings may be then modified for a more precise delineation of specific reaches of critical fish habitat.

The next step to assessing essential fish habitat for anadromous fishes was the inclusion of hydrodynamics with habitat suitability to better simulate a dynamic system. To reach

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this end, a hydrodynamic model was modified to include several factors with potential importance to survival: spawning location, habitat suitability, discharge and hatching rates (temperature dependent). This model allows for the calculation of an index of habitat exposures by a cohort that may be altered by applying different values for the above list factors. Information from the previous chapters was used for the development of the model, including habitat suitability ratings for upstream, mid-river and downstream segments of the rivers. Hydrodynamic impacts on American shad were further explored by correlating abiotic parameters with the juvenile Alosa index (JAI) from 1991-1999, used as an estimate of juvenile shad recruitment. For each of the months May – June, mean, minimum, maximum discharge, number of days discharge was within 25 and 75% quartiles per month, total monthly precipitation and average monthly water temperature were correlated with the natural log of juvenile shad indices for the Mattaponi and Pamunkey rivers.

Typically, the hydrodynamic model results indicated low and average flow values contributed to high relative habitat experience values for a population, while extreme high flows decreased these values. This pattern is not apparent in correlations between April discharge and JAI, in fact at times an opposite trend of increasing JAI with increasing discharge is evident. This may be in part due to the lack of significant correlation between April discharge and the JAI. May discharge values had the most consistent correlations with JAI and should be utilized in the hydrodynamic model for more accurate matching to JAI trends. Since May flows are on average lower than April

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flows, low and average April flows (8.7 and 20.6 m^3/s) are similar to average and high May flows (14.5 and 31.1 m^3/s), and result in high habitat experience values. In agreement with the model, declines in JAI occurred in the Pamunkey River in extreme high flows in May (> 60m^3/s) correspond to the scenario that extreme high flow events decrease habitat experience index values. Additionally, higher percentages of juvenile shad with May and June hatch dates than in other months in annual juvenile surveys support the hydrodynamic model results that low to average flows result in higher habitat experience indices than do high flows.

Alternatively, limitations to the hydrodynamic model and correlation analysis may have caused disparity between the results. The hydrodynamic model may not accurately depict shad distributions, other factors not addressed in this study may alter habitat suitability values, and/or correlations may not describe consistent trends. If shad eggs sink and lodge in substrate or structure, they are made unavailable to tides and discharge during development and the hydrodynamic model could not properly depict their distributions. Since, habitat suitability values were based on presence of eggs/larvae from 1997-1999 collections, a description of habitat suitability based on distributions over a longer time period, with the inclusion of additional parameters such as prey availability is necessary to refine the model. Similarly, the hydrodynamic model addressed egg and larval stages, while hydrographic correlations were examined using the juvenile Alosa indices, thus factors of importance to juvenile stages not addressed by the hydrodynamic model (e.g. predator and prey abundance and distribution) may elicit

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differing trends in discharge impacts. Lastly, since spurious correlations are possible, trends between discharge and the JAI need to be reassessed in the future when longer-term data-sets are available, and causal relationships established before more definitive conclusions may be deduced.

In its current form, the hydrodynamic model only has utility as a tool for evaluating hypotheses regarding current concepts of interactions between shad propagules and their environment in space and time. It serves to illustrate the potential impacts of spatial variations in habitat suitability. It may eventually be suitable for evaluating the consequences of different spawning strategies (in space and time). Hatchery release locations can then be appraised to avoid excessive larval loss from the system and/or transport to unfavorable nursery habitats. Because the model provides a spatial and temporal framework for assessing processes affecting recruitment, it can serve to integrate future advances in understanding about shad habitat utilization.

Because of the inconsistency in hydrographic controls between rivers, and differences in egg and larval densities between rivers other possible influences on the survival of the early life stages of shad were explored, including biotic, morphological, land use and water quality. The two rivers have similar land use, water quality and morphological structure based on the parameters examined in this study. There may be differences in prey and/or predator abundance between these rivers that could impact the growth and mortality of the early life stages, but the data were not available to sufficiently explore

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this possibility. Future work should address the abundance and distribution of potential prey and predator species to discern impact of biotic controls on shad in the Mattaponi and Pamunkey rivers.

Overall, this study is a step towards a watershed habitat assessment tool for essential fish habitat. It proceeds beyond typical habitat suitability index models which do not include physical habitat, riparian or landscape features. Furthermore, a conceptual hydrodynamic model was developed which linked habitat suitability and hydrodynamics within coastal plain systems. Through the course of developing these protocols, the relationship of habitat parameters with the distribution of eggs were observed and analyzed. As future research attains additional information on the functional relationship of egg and larval density with habitat features, it may be incorporated in this analysis for reevaluation and refinement of habitat suitability assessment. This may in turn lead to clarity on the potential influences driving varying productivity in these two rivers.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Literature Cited

Aiken, M.L. in prep. Construction, analysis and use of an index of abundnace for juvenile American shad. Thesis. Virginia Institute of Marine Science. Gloucester Point, VA.

Atlantic States Marine Fisheries Commission. April 1999. Amendment 1 to the Interstate Fishery Management Plan for Shad and River Herring. Washington D.C. No. 35, 76p.

Auld, A.H. and J.R. Schubel. 1978. Effects of suspended sediments on fish eggs and larvae: a laboratory assessment. Estuarine Coastal Marine Science 6: 153-164.

Austin, H.M., A.D. Estes and D.M. Seaver. 2000. Estimation of juvenile striped bass relative abundance in the Virginia Portion of Chesapeake Bay. Annual Progress Report. Virginia Institute of Marine Science, Gloucester Point. Virginia. 32p.

Austin, H.M. and J.F. Walter. 1998. Food Habits of large striped bass in the lower Chesapeake Bay and its tributaries March 1997-May 1998. Final report to the Marine Recreational Fisheries Advisory Board and Commercial Fisheries Advisory Board, VMRC. Contract number RF-97-08 and CF-97-08.

Beach, N.W. 1960. A study of the planktonic rotifers of the Oequeoe River system, Presque Isle County, Michigan. Ecological Monographs 30: 339-357.

Benke, A. C., R.L. Henry, III, D.M. Gillespie and R. J. Hunter. 1985. Importance of snag habitat for animal production in southeastern streams. Fisheries 10(5): 8-13.

Beschta, R.L. 1991. Stream habitat management for fish in the northwestern United

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

States: The role of riparian vegetation. American Fisheries Society Symposium 10: 3-58.

Bigelow, H. B. and W.W. Welsh. 1925. Fishes of the Gulf of Maine. U.S. Bureau of Fisheries Bulletin 40(1): 567p.

Bilkovic, D. M., J.E. Olney and C.H. Hershner. *in review*. Spawning of American shad (*Alosa sapidissima*) and Striped bass (*Morone saxatilis*) in the Mattaponi and Pamunkey Rivers, Virginia. Fisheries Bulletin.

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dolloff, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest. Pages 143-190 *In*: E.O. Salo and T.W. Cundy (eds.). Streamside management: forestry and fishery interactions. Contribution No. 57. Coll. For. Res. Univ. Wash. Seattle.

Boynton, W.R., T.T. Polgar and H.H. Zion. 1981. Importance of juvenile striped bass food habits in the Potomac estuary. Transactions of the American Fisheries Society 110: 56-63.

Bradford, A.D., J.G. Miller and K. Buss. 1968. Bio-assays on eggs and larval stages of American shad *Alosa sapidissima*. *In:* Suitability of the Susquehanna River for restoration of shad. U.S. Dept. Int., Maryland Bd Nat. Res., New York Conservation Department and Pennsylvania Fish Commission. p. 52-60.

Carlson, F. T. 1968. Suitability of the Susquehanna River for restoration of shad, U.S. Dept. Int., Maryland Bd. Natur. Res., New York Conserv. Dept., and Pennsylvania Fish Comm.: 60.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Chittenden, M.E., Jr. 1969. Life history and ecology of the American shad, *Alosa sapidissima*, in the Delaware River. Ph.D. thesis, Rutgers University, New Brunswick, New Jersey.

Chittenden, M.E., Jr. 1973. Effects of handling on oxygen requirements of American shad (*Alosa sapidissima*). Journal of Fisheries Research Board of Canada 30: 105-110.

Chittenden, M.E., Jr. 1976. Weight loss, mortality, feeding, and duration of residence of adult American shad, *Alosa sapidissima*, in freshwater. Fishery Bulletin 74: 151-157.

Correll, D.L. 1983. N and P in soils and runoff of three coastal plain land uses. *In* R.Lowrance, R. Todd, L.Asmussen, and R. Leonard (eds.), Nutrient cycling in Agricultural Ecosystems. University of Georgia Agricultural Experiment Station Special Publication 23, Athens, Georgia.

Correll, D.L., T.E. Jordan and D.E. Weller. 1992. Nutrient flux in a landscape: effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters. Estuaries 15(4): 431-442.

Crance, J.H. 1987. Guidelines for using the Delphi technique to develop habitat suitability index curves. U.S. Fish and Wildlife Service Biological Report 82(10.134). 21p.

Crecco, V.A. and M.M. Blake. 1983. Feeding ecology of coexisting larvae of American shad and blueback herring in the Connecticut River. Transactions of the American Fisheries Society 112: 498-507.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Crecco, V. A. and T. F. Savoy. 1984. Effects of fluctuations in hydrographic conditions on year-class strength of American shad (*Alosa sapidissima*) in the Connecticut River. Canadian Journal of Fisheries and Aquatic Sciences 41: 1216-1223.

Crecco, V.A. and T. Savoy. 1985. Effects of biotic and abiotic factors on growth and relative survival of young American shad in the Connecticut River. Canadian Journal of Fisheries and Aquatic Sciences 42: 1640-1648.

Crecco, V.A. and T. Savoy. 1987a. Review of recruitment mechanisms of the American Shad: The critical period and match-mismatch hypotheses reexamined. American Fisheries Society Symposium 1: 455-468.

Crecco, V. A. and T. Savoy. 1987b. Effects of climatic and density-dependent factors on intra-annual mortality of larval American shad. American Fisheries Society Symposium 2: 69-81.

Dadswell, M.J., G.D. Melvin and P.J. Williams. 1983. Effect of turbidity on the temporal and spatial utilization of the inner Bay of Fundy by American shad (*Alosa sapidissima*) (Pisces: Clupeidae) and its relationship to local fisheries. Canadian Journal of Fisheries and Aquatic Sciences 40 (Suppl. 1): 332-330.

Dawson, S. L. 1992. Juvenile pelagic fish communities in the Mattaponi and Pamunkey Rivers, Virginia. Department of Fisheries Science. Thesis. Williamsburg, VA, College of William and Mary: 74p.

Decamps, H. 1993. River margins and environmental change. Ecological Applications 3(3): 441-445.

Dixon, D.A., J.D. Goins and J.E. Olney. 1997. A stock assessment program for

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Chesapeake Bay fisheries development of an *Alosa* juvenile index of abundance: 1995 and 1996 index sampling results. Completion Report for contract number CF96-8. Virginia Institute of Marine Science. Gloucester Point, VA.

Fajen, A. and J.B. Layzer. 1993. Agricultural practices. Pages 257-270. In C.F. Bryan and D.A. Rutherford. editors. Impacts on warmwater streams: Guidelines for evaluation. Southern Division. American Fisheries Society. Little Rock, Arkansas.

Field, J.D. 1997. Atlantic striped bass management: Where did we go right? Fisheries 22 (7): 6-8.

Food and Agriculture Organization of the United Nations. 1995. The state of world fisheries and aquaculture, FAO.

Forman, R.T. and M. Godron. 1986. Landscape Ecology. John Wiley and Sons, New York.

Gardinier, M.N. and T.B. Hoff. 1982. Diet of striped bass in the Hudson River estuary. N.Y. Fish and Game Journal 29(2): 152-165.

Grant, G. C. and J.E. Olney 1991. Distribution of striped bass *Morone saxatilis* (Walbaum) eggs and larvae in major Virginia Rivers. Fisheries Bulletin 89: 187-193.

Gunther, T. Virginia Game and Inland Fisheries. Richmond, Virginia 23230. Personal Commun., 2000.

Heede, B.H. and J.N. Rinne. 1990. Hydrodynamic and fluvial morphologic processes: implications for fisheries management and research. North American Journal of Fisheries Management 10: 249-268.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Hoss, D.E. and G.W. Thayer. 1993. The importance of habitat to the early life history of estuarine dependent fishes. American Fisheries Society Symposium 14: 147-158.

Hubert, W.A. and S.J. Kozel. 1993. Quantitative relations of physical habitat features to channel slope and discharge in unaltered mountain streams. Journal of Freshwater Ecology 8: 177-183.

Hunter, J.R. 1981. Feeding ecology and predation of marine fish larvae, pp. 34-77. *In* R. Lasker. Marine Fish Larvae. Seattle : Washington Sea Grant : Distributor, University of Washington Press.

Isaak, D.J. and W.A. Hubert. 1997. Integrating new technologies into fisheries science: the application of geographic information systems. Fisheries 22(1): 6-10.

Jenkins, R.E. and N.M. Burkhead. 1994. Freshwater fishes of Virginia. American Fisheries Society. Bethesda, Maryland, 1079p.

Jessop, B.M. 1975. A review of the American shad (*Alosa sapidissima*) stocks of the St. John River, New Brunswick, with particular references to the adverse effects of hydroelectric development. Can. Fish. Mar. Serv. Resour., Dev. Branch Marit. Reg. Tech. Rep. Ser. Mar. T. 75: 1-23.

Johnson, H. M. and D.L. Belval. 1998. Nutrient and suspended solids loads, yields, and trends in the non-tidal part of five major river basins in Virginia, 1985-96. Prepared in cooperation with the Virginia Department of Environmental Quality, Chesapeake Bay Program. Richmond, Va.: U.S. Dept. of the Interior, U.S. Geological Survey; Denver, CO: Information Services.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Johnson, J.H. and D.S. Dropkin. 1992. Predation on recently released larval American shad in the Susquehanna River basin. North American Journal of Fisheries Management 12: 504-508.

Johnson, J.H. and D.S. Dropkin. 1997. Food and prey selection of recently released American shad (*Alosa sapidissima*) larvae. Journal of Freshwater Ecology 12(3): 355-358.

Jones, P.W., F.D. Martin and J.D. Hardy, Jr. 1978. Development of fishes of the mid-Atlantic Bight. An atlas of egg, larval and juvenile stages. Vol. 1. Acipenseridae through Ictaluridae. U.S. Fish and Wildlife Service. FWS/OBS-78/12.

Jongman, R.H.G., C.J.F. Ter Braak and O.F.R. Van Tongeren. 1995. Data analysis in community and landscape ecology. Cambridge University Press.

Kaiser, H. F. 1960. The application of electronic computers to factor analysis. Educational and Psychological Measurement 20: 141-151.

Karr, J.R. and D.R. Dudley. 1981. Ecological perspectives on water quality goals. Environmental Management 5: 55-68.

Karr, J.R. and I.J. Schlosser. 1978. Water Resources and the Land-Water Interface. Science. 201(4352): 229-234.

Keleher, C.J. and F.J. Rahel. 1996. Thermal limits to salmonid distributions in the Rocky Mountain region and potential habitat loss due to global warming: geographic information system (GIS) approach. Transactions of the American Fisheries Society 125: 1-13.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Klauda, R.J., S.A. Fischer, L.W. Hall, Jr. and J.A Sullivan. 1991. *In* Funderburk et al., eds. Habitat requirements for Chesapeake Bay living resources. Living Resources Subcommittee, Chesapeake Bay Program. Annapolis, MD.

Kuzmeskus, D.M. 1977. Egg production and spawning site distribution of the American shad, *Alosa sapidissima*, in the Holyoke Pool, Connecticut River, Massachusetts. MS thesis, Univ. of Mass., Amherst.

Lanka, R.P., W.A. Hubert and T.A. Weschie. 1987. Relations of Geomorphology to stream habitat and Trout standing stock in small Rocky Mountain Streams. Transactions of the American Fisheries Society 116: 21-28.

Large, A.R.G. and G.E. Petts. 1994. Rehabilitation of river margins. *In* The rivers handbook: hydrological and ecological principles, Vol. 2. Eds. P. Calow and G.E. Petts. Blackwell Scientific Publications, Oxford, England. pp. 401-418.

Leach, S.D. and E.D. Houde. 1999. Effects of environmental factors on survival, growth, and production of American shad larvae. Journal of Fish Biology 54: 767-786.

Leggett, W.C. 1976. The American shad *Alosa sapidissima*, with special reference to its migrations and population dynamics in the Connecticut River. American Fisheries Society Monograph 1: 169-225.

Leggett, W.C. and R.R. Whitney. 1972. Water temperature and the migrations of American shad. Fishery Bulletin 70: 659-670.

Leim, A.H. 1924. The life history of the shad, *Alosa sapidissima* (Wilson), with special reference to the factors limiting its abundance. Contributions to Canadian Biology and Fisheries 2: 163-284.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Lenat, D.R. and J.K. Crawford. 1994. Effects of land use on water quality and aquatic biota of three North Carolina piedmont streams. Hydrobiologia 294(3): 185-199.

Leopold, L.B. 1994. A View of the River. Harvard University Press. Cambridge, Massachusetts. 298p.

Levesque, R. C. and R. J. Reed. 1972. Food availability and consumption by young Connecticut River shad *Alosa sapidissima*. Journal of the Fisheries Research Board of Canada 29: 1495-1499.

Limburg, K.E. 1996. Growth and migration of 0-year American shad (*Alosa sapidissima*) in the Hudson River estuary: otolith microstructural analysis. Canadian Journal of Fisheries and Aquatic Sciences 53: 220-238.

Limburg, K.E. and R.M. Ross. 1995. Growth and mortality rates of larval American shad, *Alosa sapidissima*, at different salinities. Estuaries 18(2): 335-340.

Limburg, K.E. and R.E. Schmidt. 1990. Patterns of fish spawning in Hudson River tributaries: response to an urban gradient? Ecology 71(4): 1238-1245.

Lippson, A. J. and R.L. Moran., Ed. 1974. Manual for identification of early developmental stages of fishes of the Potomac River estuary. Maryland Department of Natural Resources, Baltimore, 282p.

MacDonald, M. 1887. Report of shad propagation on the Potomac River during the season of 1886. Bulletin of the U.S. Fisheries Commission. pp. 436-438.

Manooch, C.S. 1973. Food habits of yearling and adult striped bass, *Morone saxatilis*

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(Walbaum), from Albemarle Sound, North Carolina. Chesapeake Science 14(2): 73-86.

Mansueti, R.J. and H. Kolb. 1953. A historical review of the shad fisheries of North America. Maryland Dept. Research and Educ., Chesapeake Biological Laboratory Publications 97: 1-293.

Marcy B.C., Jr. 1976. Early life history studies of American shad in the lower Connecticut River and the effects of the Connecticut Yankee Plant. *In* Merriman, D. and L. M. Thorpe, Eds. The Connecticut River ecological study. American Fisheries Society Monograph. 1: 141-168.

Markle, D.F. and G.C. Grant. 1970. The summer food habits of young-of -the-year striped bass in three Virginia rivers. Chesapeake Science 11(1): 50-54.

Marzolf, G.R. 1978. The Potential Effects of Clearing and Snagging on Stream Ecosystems. Fish and Wildlife Service, Office of Biological Services, National Stream Alteration Project, Rep. FWS/OBS 78/14.

Massmann, W.H. 1952. Characteristics of spawning areas of shad, *Alosa sapidissima* ((Wilson) in some Virginia streams. Transactions of the American Fisheries Society 81: 78-93.

Massmann, W.H. 1963. Summer food of juvenile American shad in Virginia waters. Chesapeake Science 4(4): 167-171.

Massmann, W.H. and A.L. Pacheo. 1957. Shad catches and water temperatures in Virginia. Journal of Wildlife Management. 21(3): 351-352.

Maurice, K.R., R.W. Blye, P.L. Harmon and D. Lake. 1987. Increased spawning by

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

American shad coincident with improved dissolved oxygen in the tidal Delaware River. American Fisheries Society Special Symposium 1: 79-88.

McGovern, J. C. and J. E. Olney. 1988. Potential predation by fish and invertebrates on early life history stages of striped bass in the Pamunkey River, Virginia. Transactions of the American Fisheries Society 117: 152-161.

McGovern, J.C. and J.E. Olney. 1996. Factors affecting survival of early life stages and subsequent recruitment of striped bass on the Pamunkey River, Virginia. Canadian Journal of Fisheries and Aquatic Science 53: 1713-1726.

Minshall, G.W., R.C. Petersen, K.W. Cummins, T.L. Bott and J.R. Sedell. 1983. Interbiome Comparison of Stream Ecosystem Dynamics. Ecological Monographs 53(1): 1-25.

Murdy, E.O., R. S. Birdsong, J. A. Musick. 1997. Fishes of the Chesapeake Bay. Washington D.C.: Smithsonian Institution Press. 324p.

Murphy, M.L. 1995. Forestry impacts on freshwater habitat of anadromous salmonids in the Pacific Northwest and Alaska--Requirements for protection and restoration. NOAA Coastal Ocean Program Decision Analysis Series No. 7. NOAA Coastal Ocean Office, Silver Spring, MD. 156p.

Nelson, R.L., W.S. Platts, D.P. Larsen and S.E. Jensen. 1992. Trout distribution and habitat in relation to geology and geomorphology in the North Fork Humbolt River drainage, northeastern Nevada. Transactions of the American Fisheries Society 121: 405-426.

Nichols, P.R. and W. H. Massmann. 1963. Abundance, age and fecundity of shad, York River, 1953-1959. Fisheries Bulletin 63(1): 179-187.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Norfolk District Army Corps of Engineers. 1997. Environmental Impact Statement, Main Report-Vol. 1. Regional raw water study group Lower Virginia Penisula regional raw water supply plan. Norfolk, VA.

Odum 1971. Fundamentals of Ecology. Philadelphia, Saunders. 574p.

Olney, J.E. and G. Boehlert. 1988. Nearshore ichthyoplankton associated with seagrass beds in the lower Chespaeake Bay. Marine Ecological - Progress Series 45: 33-43.

Olney, J. E., J.D. Field and J.C. McGovern. 1991. Striped bass egg mortality, production, and female biomass in Virginia Rivers, 1980-1989. Transactions of the American Fisheries Society 120: 354-367.

Olney, J. E. and J. M. Hoenig. 2000. Monitoring relative abundance of American shad in Virginia's Rivers. Completion Report to the VMRC, Project: F-116-R-2.

Olney, J.E. and J.M Hoenig. *In review*. Managing a fishery under moratorium: assessment opportunities for Virginia's stocks of American shad (*Alosa sapidissima*). Fisheries. Virginia Institute of Marine Science, Gloucester Point, VA 23062.

Omernik, J.M. 1976. The Influence of Land Use on Stream Nutrient Levels. Report EPA 600/3-76-014.

Osborne, L.L. and M.J. Wiley. 1988. Empirical relationships between land use/cover and stream water quality in an agricultural watershed. Journal of Environmental Management 26: 9 –27.

Phillips, J. D. 1996. Natural and legal shoreline buffers. Estuarine Shores: Evolution,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Environments and Human Alterations. K.F. Nordstrom and C.T. Roman, eds. John Wiley & Sons, Ltd: 449-465.

Platts, W.S., W.F. Meganhan and G.W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. Gen. Tech. Rep. INT-138. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 70p.

Platts, W.S. and R.L. Nelson. 1988. Fluctuations in trout populations and their implications for land-use evaluation. North American Journal of Fisheries Management 8: 333-345.

Platts, W.S. and 12 coauthors. 1987. Methods for evaluating riparian habitats with applications to management. U.S. Forest Service General Technical Report INT-138: 1-70.

Rabeni, C.F. 1992. Habitat evaluation in a watershed context. American Fisheries Society Symposium 13: 57-67.

Rahel, F.J., C.J. Keleher and J.L. Anderson. 1996. Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: response to climate warming. Limnology and Oceanography 41(5): 1116-1123.

Rice, H.J. 1878. Notes upon the development of the shad (*Alosa sapidissima*). Rept. Comm. Fish. Maryland. pp. 95-106.

Richards, C. and G. Host. 1994. Examining land use influences on stream habitats and macroinvertebrates: a GIS approach. Water Resources Bulletin 30(4): 729-738.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Rickers, J.R., L.P. Queen and G.J. Arthaud. 1995. A proximity-based approach to assessing habitat. Landscape Ecology 10: 309-321.

Rinaldo, R. G. 1971. Analysis of *Morone saxatilis* and *Morone americana* spawning and nursery areas in the York and Pamunkey Rivers, Virginia. Thesis. Williamsburg. VA, College of William and Mary, 56p.

Rosgen, D. 1996. Applied River Morphology. Lakewood Colorado.

Ross, R.M, T.W.H. Backman and R.M. Bennett. 1993. Evaluation of habitat suitability index models for riverine life stages of American Shad, with proposed models for premigratory juveniles. U.S. Fish and Wildlife Service Biological Report 14. 26 p.

Ross, R.M., and R.M. Bennett. 1993. Morphometric differentiation of American shad and white sucker eggs from riverine sample. Journal of Freshwater Ecology 8(2): 121-126.

Ross, R.M., R.M. Bennett, and J.H. Johnson. 1997. Habitat use and feeding ecology of riverine juvenile American shad. North American Journal of Fisheries Management 17: 964-974.

Rudershausen, P.J. and J.G. Loesch. 2000. Feeding habits of Young-of Year striped bass, *Morone saxatilis*, and white perch, *Morone americana*, in lower James River, VA. Virginia Journal of Science 51(1): 23-37.

Rulifson, R. A. and C.S. Manooch III. 1990. Recruitment of juvenile striped bass in the Roanoke River, North Carolina, as related to reservoir discharge. North American Journal of Fisheries Management 10: 397-407.

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Rutherford, E.S. and E.D. Houde. 1995. The influence of temperature on cohort-specific growth, survival, and recruitment of striped bass, *Morone saxatilis*, larvae in the Chesapeake Bay. Fisheries Bulletin 93: 315-332.

Ryder, J.A. 1882. On the retardation of the development of the ova of the shad (*Alosa sapidissima*) with observations on the egg fungus and bacteria. Bulletin of the U.S. Fisheries Commission Vol. 1, pp. 177-190.

Schlosser, I.J. 1991. Stream fish ecology: A landscape perspective. Bioscience 41(10): 704-712.

Schmidt, R.E., R.J. Klauda and J.M. Bartels. 1988. Distributions and movements of the early life stages of three species of *Alosa* in the Hudson River, with comments on mechanisms to reduce interspecific competition. Pp. 141-168. *In* Smith C. L. Ed. Fisheries research in the Hudson River. The Hudson River Environmental Society. State University of New York.

Secor, D.H. and E.D. Houde. 1995. Temperature effects on the timing of striped bass egg production, larval viability, and recruitment potential in the Patuxent River (Chesapeake Bay). Estuaries 18(3): 527-544.

Sedell, J.R. and R. L. Beschta. 1991. Bringing back the "Bio" in Bioengineering. American Fisheries Society Symposium 10: 160-175.

Setzler-Hamilton, E.M., W.R. Boynton, J.A. Mihursky, T.T. Polgar and K.V. Wood. 1981. Spatial and temporal distribution of striped bass eggs, larvae and juveniles in the Potomac estuary. Transactions of the American Fisheries Society 110: 121-136.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Setzler-Hamilton, E.M., W.R. Boyton, K.V. Wood, H.H. Zion, L. Lubbers, N.K. Mountford, P. Frere, L. Tucker and J.A. Milhursky. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). NOAA Tech. Rep. NMFS 433.

Sisson, G. M., J. Shen, S.C. Kim, J. Boon and Y. Kuo. 1997. VIMS three-dimensional hydrodynamic-eutrophication model (HEM-3D): Application of the hydrodynamic model to the York River system. Special Report in Applied Marine Science and Ocean Engineering No. 341. Gloucester Point, VA, VIMS.

Stevens, D. E. and L.W. Miller. 1983. Effects of river flow on abundance of young Chinook salmon, American shad, Longfin smelt, and Delta smelt in the Sacramento-San Joaquin River system. North American Journal of Fisheries Management 3: 425-437.

Stier, D.J. and J.H. Crance. 1985. Habitat Suitability index models and instream flow suitability curves: American Shad. U.S. Fish and Wildlife Service Biological Report 82(10.88).

Strahler, A.N. 1963. The Earth Sciences. Harper and Row, New York, New York. 681p.

Tresselt, E. F. 1952. Spawning grounds of the striped bass, *Roccus saxatilis* (Walbaum), in Virginia. Bulletin of the Bingham Oceanographic Collection 14: 98-110.

United States Fish and Wildlife Service (U.S.F.W.S.) 1981. Standards for the development of habitat suitability index models. Ecological Services, USFWS, US. Dept. of Interior, Wash. D.C.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Ulanowicz, R. E., and T.T Polgar. 1980. Influences of anadromous spawning behavior and optimal environmental conditions upon Striped Bass (*Morone saxatilis*) year-class success. Canadian Journal of Fisheries and Aquatic Sciences. 37: 143-154.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. The River Continuum Concept. Canadian Journal of Fisheries and Aquatic Sciences 37(1): 130-137.

Wagner, M. 1997. Correspondence between environmental gradients and the assemblage structure of littoral fishes in the tidal portion of three Virginia Coastal Plain Rivers. Thesis. Department of Fisheries Science. Williamsburg, VA, College of William and Mary: 163p.

Walburg, C.H. 1960. Abundance and life history of the shad, St. Johns River, Florida. U.S. Fish and Wildlife Service, Fishery Bulletin 60: 487-501.

Walburg, C.H. and P.R. Nichols. 1967. Biology and management of the American shad and the status of fisheries, Atlantic coast of the United States, 1960. U.S. Fish and Wildlife Service, Special Science Report - Fish 550.

Wallace, J. B. and A.C. Benke 1984. Quantification of wood habitat in subtropical coastal plain streams. Canadian Journal of Fisheries and Aquatic Sciences 41: 1643-1652.

Walters, C.J. and Collie J.S. 1988. Is research on environmental factors useful to fisheries management? Canadian Journal of Fisheries Aquatic Sciences 45(10): 1848-1854.

Wang, L., J. Lyons and P. Kanehl. 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. Fisheries 22(6): 6-12.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Wang, L., J. Lyons and P. Kanehl. 1998. Development and evaluation of a habitat rating system for low-gradient Wisconsin streams. North American Journal of Fisheries Management. 18: 775-785.

Weaver, L.A. and G.C. Garman. 1994. Urbanization of a watershed and historical changes in a stream fish assemblage. Transactions of the American Fisheries Society 123(2): 162-172.

Williams, R.O. and G.E. Bruger. 1972. Investigations on American shad in the St. Johns River. Florida Department of Natural Resources Marine Research Laboratory Technical Series 66: 1-49.

Zimmer, D.W. and R. W. Bachmann. 1978. Channelization and invertebrate drift in some Iowa streams. Water Resources Bulletin 14(4): 868-883.

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