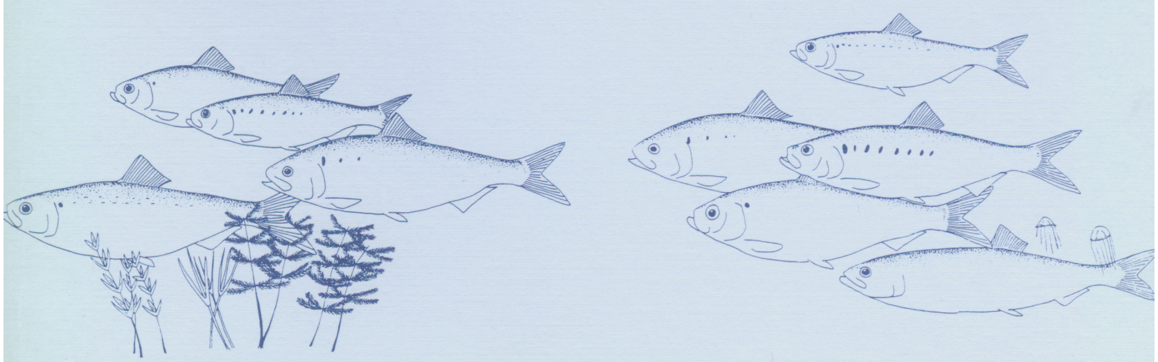
Anadromous *Alosa* Symposium

TIDEWATER CHAPTER
American Fisheries Society

1994



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A Symposium on Anadromous *Alosa*

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Anadromous *Alosa* Symposium

Edited by

John E. Cooper
Richard T. Eades
Ronald J. Klauda
Joseph G. Loesch

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Preface

The purpose of this symposium was to bring together the scientists and investigators that were involved with various aspects of anadromous *Alosa* species along the East Coast of the United States and Canada. It was our hope, that through presentation and discussion of a wide range of research endeavors, we could foster a greater understanding and appreciation of the work that is currently being done and to identify those areas that are in need of investigation. The value of this research will be in its scientific credibility. Each paper in this volume was subjected to peer review, another review by each session moderator, and a final review by the senior editor: as the last person in this chain, any errors that remain are his. The editors would like to thank the following reviewers for their comments:

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Introduction

Anadromous *Alosa* were an important source of protein for native Americans and the early colonists along the East Coast of North America and were extensively utilized by the Colonial troops during the American Revolution. George Washington was an avid angler for shad along the banks of the Potomac River. The commercial fishery reached its peak in the United States between 1895 and 1900 after which the populations of *Alosa* declined swiftly. In 1949, the Atlantic States Marine Fisheries Commission asked the federal government to investigate the decline of American shad, the largest and perhaps best known member of the herring family. Congress authorized the U.S. Fish and Wildlife Service to conduct a ten year study of the shad. In 1960, that study concluded that shad could probably not be restored to the abundance present at the beginning of the 20th century and laid the blame for the shad population decline on changes in spawning and nursery habitat from human intervention, physical and chemical changes in the river environments from deforestation of watersheds, siltation, pollution and dam construction.

Anadromous *Alosa* undergo great physiological changes in making the transition from marine to fresh water. This physiological stress may be exacerbated by the environmental conditions that anadromous *Alosa* now face in many of their spawning streams. During the past thirty years many improvements have been made in water quality, fish passages around dams, and there has been a general increase in awareness of how humankind's activities have accelerated the decline of many species. In the present age the technology exists to reverse the population decline of *Alosa* but do we know enough about the biology of the anadromous *Alosa* to effect the proper changes?

In 1990, several Tidewater Chapter members, led by Rick Eades, decided to hold a symposium on the present status of anadromous *Alosa* where investigators from the Atlantic coast of North America could present their research in an informal, chapter-meeting atmosphere. The goal of the symposium was to bring together various agencies and institutions that were conducting *Alosa* research that might not interact with each other in a more formal setting. The symposium was held at the Clarion Resort and Conference Center in Virginia Beach, Virginia, on 14-15 January 1993, in conjunction with a joint meeting with the Virginia Chapter.

The symposium was organized within several broad topics: life history and biology, stock assessment and management, fish passage, commercial and recreational fisheries, culture and stocking, and ecological roles in freshwater systems. Twenty-eight papers were presented, 14 of which are published in this volume. Many of the presentations were of work in progress (or were presented as posters) and have been included in these published proceedings only as abstracts.

In addition to the technical presentations, the 150 registered participants enjoyed a behind-the-scenes tour of the Virginia Marine Science Museum, the site of the evening dinner and social. The Museum holds several fresh and saltwater aquaria (up to 50,000 gallons) with a variety of fish and invertebrates. There are also ecological, historical, and cultural exhibits.

The Tidewater Chapter would like to thank our financial contributors whose generosity made the symposium possible, the staff of the Virginia Marine Science Museum, and the volunteers who assisted in organizing and running the symposium.

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Anadromous *Alosa* Symposium, 1994, pp. 1-6

History Of *Alosa* Fisheries Management: Virginia, A Case Study[1]

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Abstract.—Accounts in colonial times of fishes in the estuaries and open freshwater systems of the east coast are replete with statements about the great abundance and desirability of American shad *Alosa sapidissima* and river herring *Alosa* spp. Many of those involved in the early shad fisheries were large plantation owners. Thomas Jefferson brought shad to Monticello, and George Washington ran a shad fishing business, and leased fishing rights and privileges on his land on the Potomac River. The obstruction of rivers to harness water power for mills led to a great reduction or extirpation of the anadromous runs. Concern about the plight of the anadromous stocks led to legislation requiring fish passage facilities. In 1623 the first fishery law in the Colonies (known as the Plymouth Colony Fish Law) was passed for the protection of alewives *(A. pseudoharengus)*. In 1680, the first law in Virginia protecting fish was passed by the House of Burgesses. Enforcement of the laws was most often lax or absent. The loss of ancestral spawning grounds due to dams and other obstructions gained ardent attention when a serious depletion of the striped bass *Morone saxatilis* stocks in Chesapeake Bay was recognized in the late 1970's. The necessary construction and the removal of obstructions to permit access to the lost spawning grounds is presently in progress in Virginia and other coastal states. In contrast, the ocean-side fishery of Virginia, and such fisheries of other states from North Carolina to New Jersey, are detrimental activities. The fisheries are conducted on the premise that the American shad captured were destined for spawning grounds farther north, not in the state where captured. It is a rapacious attitude which precludes sensible intrastate management for the collective good of the stocks. A federal interjurisdictional act, similar to that enacted for striped bass, appears to be necessary for the revitalization of *Alosa* stocks.

Accounts in colonial times of fishes in the estuaries and open freshwater systems of the east coast are replete with statements about the great abundance and desirability of American shad *Alosa sapidissima* and herring; the term *herring* in colonial times included the alewife *A. pseudoharengus* and blueback herring *A. aestivalis*, which at the present time are collectively referred to as river herring. Prior to the arrival of the settlers in the early 1600's, the Aucocisco Indians, who lived near the Presumpscot Falls, Maine (then part of the Massachusetts Bay Colony), caught huge quantities of shad, alewives, and salmon which were used for food and fertilizer (DeRoche 1967).

Belding (1921) recounts what Thomas Morton wrote in his *New English Canaan* (1632) regarding river herring in Massachusetts:

> ... OF HERRING THERE IS A GREAT STORE, FAT AND FAIR, AND TO MY MIND AS GOOD AS ANY I HAVE SEEN, AND THESE MAY BE PRESERVED AND MADE A GOOD COMMODITY ...

There was a general pattern throughout the coastal colonies regarding the abundance of anadromous fish stocks. A plethora of fishes, then construction of dams to harness water power for mills, and, subsequently, a great reduction or extirpation of the anadromous runs. Concern about the plight of the anadromous stocks led to legislation requiring fish passage facilities, but enforcement of the laws was often lax or absent.

In 1623 the first fishery law in the Colonies (known as the Plymouth Colony Fish Law) was passed for the protection of alewives (Belding 1921). Between 1682 and 1743 a series of laws were enacted for the construction and maintenance of fish passage facilities, and for regulation of the fisheries. In 1745, however, mill owners through political pressure secured a proviso eliminating fishways if the fish did not pass upstream in adequate numbers to be of greater benefit than the loss due to diminished water power. In addition, no dam owner had to keep open any passageway if there were no longer runs of alewives, shad, or salmon (Belding 1921). Armed conflict between the Aucocisco Indians, led by Chief Polin of the Rockomeecook Tribe, and the white settlers in Maine began in 1739 because dams built by the settlers blocked the migration of salmon to Sebago Lake (DeRoche 1967). The fighting did not entirely end until Chief Polin was killed in 1756.

[1] Virginia Institute of Marine Science Contribution No. 1848
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Virginia, A Case Example

Legislation and Management

The pattern of anadromous fish abundance, dam construction, stock reduction, fishway legislation, and circumvention of the legislation, or an indifferent attitude toward enforcement of the fishways laws was well defined in Virginia's management policies until recent years.

Much of the information regarding Virginia's anadromous fishes in colonial days was published by the Virginia Commission of Fisheries (VCF) in 1875, the first year of the Commission's existence. Before the colonists came to Virginia, the native Americans in Virginia caught American shad in the rivers and streams in large quantities using seine nets made from bushes (Walburg and Nichols 1967). The shad were so plentiful as they swam on the flats that children could spear them with sticks (VCF 1875). The early settlers utilized river herring and shad as a major food supply, and that the fish could be easily stored when salted added to their value (VCF 1875; Walburg and Nichols 1967).

In 1588, Thomas Hariot wrote that during the months of February through May in Virginia, herring were

> ...MOST PLENTIFUL, AND IN BEST SEASON, WHICH WE FOUND TO BE MOST DELICATE AND PLEASANT MEAT (IN DE BRY 1590)

Many of those involved in the early shad fisheries were large plantation owners. Thomas Jefferson brought shad to Monticello, and George Washington ran a shad fishing business, and leased fishing rights and privileges on his land on the Potomac River (Mansueti and Kolb 1953).

Concern for the protection of the fishery resources has long been evident in Virginia's laws. In 1680, the first law in Virginia protecting fish was passed; it prohibited the striking of fish with "giggs and harp-irons" in the waters of Gloucester, Middlesex, and Lancaster counties (VCF 1875). For some reason, unknown today, the law was repealed the next session, but at the same time a law was passed that:

> ...PROHIBITED THE KILLING OF WHALES IN CHESAPEAKE BAY, WITHOUT CONSENT OF THE GOVERNOR. THIS WAS DICTATED BY HYGIENIC CONSIDERATIONS. THE WHALES, IT IS PRESUMED, BEING NUMEROUS, AND KILLED IN WANTONNESS, WOULD FLOAT ASHORE AND SPREAD AN UNPLEASANT STENCH THROUGH THE COUNTRY SIDE, AND IT WAS APPREHENDED THE HEALTH OF THE INHABITANTS MIGHT SUFFER. WE FIND A PERMIT GIVEN BY GOVERNOR GOOCH TO FIVE OR SIX GENTLEMEN TO GO TO THE CHESAPEAKE TO KILL WHALES. POSSIBLE THESE MAMMALS OF THE FINNY RACE, WHEN THEY HEAR OF THE DISCOVERY OF KEROSENE, MAY RETURN TO THEIR ANCIENT SPOUTING GROUNDS.

Apparently, members of the House of Burgesses enjoyed blithe moments.

Beginning about 1740, Virginians became concerned about the depletion of the fish stocks, and from that time until the Revolutionary War (1775-1783), laws were passed in Virginia requiring the removal of the obstructions or the building of fish passages. A typical example of this is an act, passed in 1761, concerning a dam built on Rockfish River, a tributary of the James River in Nelson County, formerly part of Amherst County (VCF 1875):

> IT BEING REPRESENTED THAT ALLAN HOWARD, A GENTLEMAN, HATH ERECTED A MILL ON ROCKFISH RIVER IN AMHERST CO, THE DAM WHEREOF HATH ENTIRELY OBSTRUCTED THE PASSAGE OF FISH UP SAID RIVER, TO THE GREAT LOSS AND PREJUDICE OF THE INHABITANTS ON THE SAME, ... SAID HOWARD SHOULD IN TWO MONTHS PULL DOWN AND DESTROY HIS SAID MILL-DAM AND MILL-HOUSE ... AND THAT NO DAM ON SAID RIVER BELOW THE FORKS NEAR SAM MORRIL'S SHOULD BE LAWFUL.

Many of the early fish passage facilities were unsuccessful. In 1771, an act was passed defining the type of fish passages to be built and the times when they were to be kept open (VCF 1875):

> THAT A GAP BE CUT IN THE TOP OF THE DAM CONTIGUOUS TO THE DEEPEST PART OF THE WATER BELOW THE DAM, IN WHICH SHALL BE SET A SLOPE TEN FEET WIDE, AND SO DEEP THAT THE WATER MAY RUN THROUGH IT EIGHTEEN INCHES BEFORE IT WILL THROUGH THE WASTE, OR OVER THE DAM; THAT THE DIRECTION OF THE SAID SLOPE BE SO, AS WITH A PERPENDICULAR, TO BE DROPPED FROM THE TOP OF THE DAM, WILL FORM AN ANGLE OF AT LEAST SEVENTY-FIVE DEGREES, AND TO CONTINUE IN THE DIRECTION TO THE BOTTOM OF THE RIVER, BELOW THE DAM, TO BE PLANKED UP THE SIDES TWO FEET HIGH; THAT THERE BE PITS OR BASINS BUILT IN THE BOTTOM, AT EIGHT FEET DISTANCE, THE WIDTH OF THE SAID SLOPE, AND TO BE TWELVE INCHES DEEP, AND THAT THE WHOLE BE TIGHT AND STRONG; WHICH SAID SLOPE SHALL BE KEPT OPEN FROM THE TENTH DAY OF FEBRUARY TO THE LAST DAY OF MAY, ANNUALLY, AND ANY OWNER NOT COMPLYING TO FORFEIT FIVE POUNDS TOBACCO A DAY.

Due to the onset of the Revolutionary War this law was never enforced and the fish passage design was not tested.

In the Virginia Code of 1849, the Virginia legislature reaffirmed its right to restrict the building of dams (VCF 1875):

> WHATEVER POWER IS RESERVED TO THE LEGISLATURE BY ANY ACT HERETOFORE PASSED, TO ABATE ANY DAM OR OTHER WORKS IN A WATER-COURSE, OR IMPROVE ITS NAVIGATION, SHALL CONTINUE IN FULL FORCE.

The Virginia Commission of Fisheries in the late 1800's was enthusiastic about the fishing potential in the James River, and concerned about dams being built on it. In its first annual report in 1875, the VCF stated of the James River:

> IT POSSESSES EVERY ADVANTAGE FOR THE PRODUCTION OF AN IMMENSE QUANTITY OF FISH OF VARIOUS KINDS, ALL OF WHICH ADVANTAGES ARE LOST BY THE GREAT NUMBER OF DAMS WHICH BAR ITS COURSE ABOVE THE TIDE. ...DAMS, ALSO, BESIDES ARRESTING THE ASCENT OF ANADROMOUS FISH AND WITHHOLDING THAT "PROVIDENTIAL SUCCOR" FROM ALL THE PEOPLE ON THE STREAM, TEND TO DENUDE THE RIVERS OF ALL THEIR NATIVE FISHES. WITH THE FIRST FRESH IN THE FALL, THE LARGEST AND BEST OF THESE DAMS PREVENT THEIR REASCENT NEXT SPRING. IN THIS WAY THE JAMES RIVER HAS BEEN STRIPPED, AND FOR ITS VOLUME AND EXTENT, IS PERHAPS, THE POOREST STREAM IN FISH ON THE CONTINENT.

Prior to the obstruction of the James River by dam-building, shad and river herring reportedly ascended about 580 km to the junction of Jackson and Cowpasture rivers near the Blue Ridge Mountains in Botetourt County, Virginia (McDonald 1887), and far up all the principal tributaries (VCF 1875).

It appears that the Virginia legislature of 1870-71 began, and then aborted, a project to alleviate the problem of obstructions on the rivers. In a letter dated October 2, 1872, and published by the U.S. Commission of Fish and Fisheries, McKennie (1873) wrote concerning obstructions on the rivers in Virginia:

> I HAVE BEEN MUCH INTERESTED IN THE QUESTION FOR SEVERAL YEARS, BUT I FEAR THAT LITTLE CAN BE DONE UNTIL SOME CUNNING LEECH IS ABLE TO APPLY SOME PLASTER TO OUR PEOPLE WHICH SHALL AROUSE THEM TO A SENSE OF THEIR DUTY TO THEMSELVES AND THEIR CHILDREN. THE PROJECT STARTED IN A SMALL WAY BY THE LEGISLATURE OF 1870-71 WAS DROPPED BY THAT OF 1871-72.

By 1875 there were 21 dams, with an average height of 14.5 feet, on the James River from Richmond to Buchanan (in Botetourt County), a distance of 327.5 km (VCF 1875); by 1882 the number had increased to 23 (VCF 1882). These dams had been the property of the James River and Kanawha Canal Company, but ownership was transferred by the Virginia Assembly to the Richmond and Allegheny Railroad, subject to the construction by the railroad of suitable fishways for the passage of shad over all the dams maintained by them. In 1882 only one fishway had been constructed, that over Bosher dam, and it was incomplete (VCF 1882).

In 1930 the General Assembly enacted Virginia Code section 29-151, requiring the owners of dams and other obstructions which may interfere with the free passage of fish to provide a suitable fish ladder. The act was amended in 1942, 1950, and again in 1958, and then read as follows:

> 29-151. DAMS AND FISH LADDERS; INSPECTION OF.—ANY DAM OR OTHER THING IN A WATER COURSE, WHICH OBSTRUCTS NAVIGATION OR THE PASSAGE OF FISH, SHALL BE DEEMED A NUISANCE, UNLESS IT BE TO WORK A MILL, MANUFACTORY OR OTHER MACHINE OR ENGINE USEFUL TO THE PUBLIC, AND IS ALLOWED BY LAW OR ORDER OF COURT. ANY PERSON OWNING OR HAVING CONTROL OF ANY DAM OR OTHER OBSTRUCTION IN ANY OF THE STREAMS OF THIS STATE ABOVE TIDEWATER WHICH MAY INTERFERE WITH THE FREE PASSAGE OF FISH, SHALL PROVIDE EVERY SUCH DAM OR OTHER OBSTRUCTION WITH A SUITABLE FISH LADDER, SO THAT FISH HAVE FREE PASSAGE UP AND DOWN THE STREAMS DURING THE MONTHS OF MARCH, APRIL, MAY AND JUNE OF EACH YEAR, AND MAINTAIN AND KEEP THE SAME GOOD REPAIR, AND RESTORE IT IN CASE OF DESTRUCTION; PROVIDED, HOWEVER, THAT THIS SECTION SHALL NOT APPLY TO THE MEHERRIN RIVER WITHIN THE COUNTIES OF BRUNSWICK AND GREENVILLE, NOR THE MEHERRIN RIVER WITHIN OR BETWEEN THE COUNTIES OF LUNENBURG AND MECKLENBURG, NOR TO THE NOTTOWAY RIVER BETWEEN THE COUNTIES OF LUNENBURG AND NOTTOWAY, NOR TO ABRAM'S CREEK IN SHAWNEE DISTRICT, FREDERICK COUNTY, NOR TO THE JAMES RIVER BETWEEN THE COUNTIES OF BEDFORD AND AMHERST, NOR ANY STREAMS WITHIN THE COUNTIES OF AUGUSTA, LUNENBURG, MECKLENBURG, LOUISA, BUCKINGHAM, HALIFAX, MONTGOMERY, PULASKI, FRANKLIN, RUSSELL, TAZEWELL, GILES, BLAND, CRAIG, WYTHE, CARROLL AND GRAYSON, NOR TO THAT PART OF ANY STREAM THAT FORMS A PART OF THE BOUNDARY OF HALIFAX AND FRANKLIN COUNTIES; PROVIDED HOWEVER, THAT NO FISH LADDERS SHALL BE REQUIRED ON DAMS TWENTY FEET OR MORE IN HEIGHT OR ON SUCH DAMS AS THE COMMISSION MAY DEEM IT UNNECESSARY ON WHICH TO HAVE LADDERS. ANY PERSON FAILING TO COMPLY WITH THIS PROVISION SHALL BE FINED ONE DOLLAR FOR EACH DAY'S FAILURE; AND THE

CIRCUIT COURT OF THE COUNTY OR THE CORPORATION COURT OF THE CITY IN WHICH THE DAM IS SITUATED, AFTER REASONABLE NOTICE, BY RULE OR OTHERWISE, TO THE PARTIES OR PARTY INTERESTED AND UPON SATISFACTORY PROOF OF FAILURE, SHALL CAUSE THE FISHWAY TO BE CONSTRUCTED, OR PUT IN GOOD REPAIR AS THE CASE MAY BE, AT THE EXPENSE OF THE OWNER OF THE DAM OR OTHER OBSTRUCTION. IT SHALL BE THE DUTY OF THE SAME WARDEN TO MAKE A PERSONAL INSPECTION OF DAMS AND RIVERS IN HIS RESPECTIVE COUNTY OR CITY IN THE MONTHS OF APRIL AND OCTOBER OF EACH YEAR AND REPORT TO THE CIRCUIT COURT OF THE COUNTY OR THE CORPORATION COURT OF THE CITY ANY VIOLATION OF THIS SECTION. (1930, P.651; MICHIE CODE 1942, 3305(42); 1950, P.891; 1958, C. 607.)

Virginia Code section 29-151 was never strictly administered. Although there were high and low periods of abundance of American shad and other important commercial and recreational species, most everyone was satisfied with the prevailing conditions - a period of low abundance for a species would be attributed to a downturn in a natural "cycle" of abundance.

Commercial Fisheries

Haul seines were used almost exclusively in the early days of the commercial fisheries for American shad, but about 1835 gill nets were introduced, and have since become a major gear in the Chesapeake Bay shad fisheries (Walburg and Nichols 1967). Pound nets were introduced to the area in 1858, and reached their peak in use in 1930 (Kriete and Merriner 1978). At the present time, however, almost all landings of American shad in Virginia are from gill nets (anchor, drift, and stake). Pound net catches of American shad appear related to stock density. During the period 1973 to 1977, pound nets accounted for 22% of the total landings of American shad. In contrast, in the period 1983 to 1987, a period of low stock abundance as indicated by a 50% decrease in the average landings relative to the 1970's period, pound nets accounted for only 5% of the total landings of American shad. There was little difference in pound net fishing effort in the two periods, indicating that American shad prefer to migrate in mainstream waters but some must spread to shoal waters when abundance is high. Leggett (1976) reported that American shad in the Connecticut River preferred deeper channel waters.

The shad fishery of Chesapeake Bay gained importance about 1869, and developed greatly in the ensuing years. Due to decreased landings, an artificial hatching program was begun in 1875 by the U.S. Fish Commission and Virginia Commission of Fisheries. In 1879 the fishery began to improve, and this increase led biologists to believe that the shad fishery was largely dependent upon artificial propagation. The hatchery program was expanded, but later studies showed that the upsurge could not be correlated with the output from artificial stocking (Mansueti and Kolb 1953). In 1880 the tributaries of the Chesapeake Bay yielded more than 2,268 metric tons (mt) of shad. Virginia ranked second to New Jersey in shad landings in 1896 with 4,990 mt. In 1908, Virginia's catch of 3,311 mt of American shad made it the most important fish caught in Virginia and comprised about one fourth of all American shad taken in the United States. In the early 1900's a decline began in the numbers of shad harvested despite improved hatching methods and increased numbers of fry released (Mansueti and Kolb 1953). Heavy fishing pressure possibly offset the potential gains of the hatchery operations, or there was poor survival of the shad fry.

There was a major loss of spawning grounds with the construction of dams on Virginia rivers. Most of this activity on large river systems was completed by the early 1900's. In the Chickahominy River, American shad spawned from above the junction with the James River to the vicinity of Providence Forge, a distance of about 50 km (Walburg and Sykes 1957). With the construction of the Walker Dam in 1943, anadromous fishes were limited, for the most part, to the lower 27 km of the river. Occasional access to historic spawning grounds occurs for some fishes when exceptionally high tides cover the low-head dam for a brief period, and also during the infrequent use of the self-operated boat lock in Walker Dam. In 1896, before the dam was built, the Chickahominy River contributed 30% of the total American shad catch in the James River watershed; however, in 1960 it contributed only 13% (Walburg and Nichols 1967), and there is no American shad fishery on the Chickahominy River today. The loss of the fishery appears related to the loss of the spawning grounds, since the fishery was conducted below the site of the dam.

The loss of ancestral spawning grounds due to dams and other obstructions gained attention when a serious depletion of the striped bass *Morone saxatilis* stocks in Chesapeake Bay was recognized in the late 1970's. In Virginia, a feasibility study of fish passage facilities over the dams in the James River was conducted (Atran et al. 1983); the necessary construction for access to the lost spawning grounds is in progress under the auspices of the Virginia Department of Game and Inland Fisheries.

Ocean-Side Intercept Fishery

Although the American shad and river herring fishery management plan calls for the enhancement of the traditional (riverine) *Alosa* fisheries, an ocean-side gill net fishery has rapidly developed. In 1980, the riverine fisheries accounted for 90%, and the ocean-side intercept fishery 10%, of the American shad landed in Virginia. Since then the riverine portion of the landings steadily decreased and by 1992, the percentages of 1980 were reversed (Table 1).

The American shad intercept fishery is wasteful in that the fish are captured before they can spawn, and before the roe develop and have market value. Furthermore, by the time American shad are available to the riverine fishermen, the market value is often greatly depressed. The relatively stable landings in the offshore fishery in recent years appear to indicate a stable fishery; however, the apparent stability may be due to the presence of multiple stocks. A major step toward the enhancement of the American shad populations and the riverine shad fisheries would be the regulation and allocation of landings by gear and location.

The ocean-side fishery of Virginia, and such fisheries of other states from North Carolina to New Jersey, is conducted on the premise that the American shad captured were destined for spawning grounds farther north, not in the state where captured. The present evidence for this premise is not strong; regardless, it is a rapacious attitude which precludes sensible intrastate management for the collective good of the stocks. A federal interjurisdictional act, similar to that enacted for striped bass, appears to be necessary for the revitalization of *Alosa* stocks.

A brief account of the history of the management of *Alosa* stocks has been given. A thorough compilation remains for those persons with the time and talent to search out correspondence, diaries, and business logbooks and receipts, many of which preceded state and federal fishery reports.

TABLE 1.— American shad landings in Virginia by area of harvest. mt = metric tons. (Source: Dr. Erik Barth, Virginia Marine Resources Commission).

Year	Inside Bay Mouth (mt)	Total (%)	Outside Bay Mouth (mt)	Total (%)	Total Landings (mt)
1980	398.2	90	43.5	10	441.7
1981	101.3	45	125.0	55	226.4
1982	139.8	53	125.6	47	265.5
1983	211.0	69	94.2	31	305.2
1984	283.6	49	292.2	51	575.8
1985	136.4	48	150.6	52	287.1
1986	98.7	38	161.3	62	259.9
1987	107.8	38	179.2	62	287.0
1988	24.7	11	194.5	89	219.2
1989	46.5	20	181.3	80	227.7
1990	58.5	28	147.4	72	205.9
1991	23.1	11	181.2	89	204.3
1992	20.3	9	196.0	91	216.3

Afterward

In January 1994, almost a year after our presentation, the Atlantic Coastal Fisheries Management Act became law. The act will require coastal states from Maine to Florida to fully implement management plans developed by the Atlantic States Marine Fisheries Commission for interjurisdictional species.

Acknowledgment

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Lethal and Critical Effects Thresholds for American Shad Eggs and Larvae Exposed to Acid and Aluminum in the Laboratory, with Speculation on the Potential Role of Habitat Acidification on Stock Status in Maryland

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Abstract.—This paper describes the results of several laboratory experiments conducted between 1985 and 1990 with early life stages of American shad *Alosa sapidissima* that were exposed to a range of acid and aluminum conditions. The goal of the experiments was to determine the sensitivity of eggs and larvae to acid and aluminum exposures and define lethal (91 to 100% direct mortality) and critical (50 to 90% direct mortality) effects thresholds. Fertilized eggs were somewhat less sensitive to acid and aluminum than were either prefeeding or feeding-stage larvae. Lethal conditions for eggs included a 48 h exposure to pH 4.1 (no aluminum) and less acidic pulses of longer duration (96 h) accompanied by moderate levels of aluminum. Prefeeding larvae appeared to be slightly less sensitive than feeding larvae. Critical conditions for eggs ranged widely from pH 5.0 (no aluminum) to pH 6.5 (with 100 g/L of aluminum). Lethal conditions for prefeeding larvae ranged widely and included a 55 h exposure to acid pulses in the mid to high pH 6 range accompanied by aluminum pulses of 57 to 460 g/L. Shorter duration (24 h) acid pulses (pH 4.0 and 5.0) with and without aluminum, were also lethal. Critical conditions for prefeeding larvae were 24 h acid pulses (pH 6.0 to 6.1) accompanied by aluminum pulses of 26 to 200 g/L. Lethal conditions for feeding larvae were not determined. Critical conditions for feeding larvae were relatively short duration (4 or 8 h) pulses of acid only (pH 6.2) and acid plus aluminum pulses (pH 6.2 with 76 g/L of aluminum) that lasted 8 h. American shad larvae were at least as and perhaps slightly more sensitive to acid and aluminum pulses in the laboratory than were fathead minnow *Pimephales promelas* larvae. A definite linkage between habitat acidification in Maryland rivers and the generally depressed status of American shad stocks has not yet been established. However, the results of these laboratory experiments, coupled with monitoring data on the buffering capacity of rivers where American shad spawn, suggest that acidic deposition may be an important anthropogenic factor in shad stock dynamics in some Maryland rivers but not in others. Three Western Shore spawning areas (Potomac, Patuxent and Susquehanna rivers and upper Chesapeake Bay) are relatively well buffered and experience few if any pH depressions and aluminum peaks that are likely to be toxic to American shad eggs and larvae. However, in poorly buffered Eastern Shore rivers like the Choptank and Nanticoke, American shad stocks are likely to be exposed, at least periodically, to storm-induced, toxic pH depressions. Hence, these stocks may recover at a much slower rate than Western Shore Maryland stocks, even if all other natural and anthropogenic stressors are removed.

Hendrey (1987) considered the acid deposition hypothesis that links stream acidification with the declines of several anadromous fish populations in Atlantic Coast estuaries as a viable topic for further study. He recommended that research address the sensitivity of anadromous and semi-anadromous species, through their life cycles, to acidity and elevated levels of aluminum, and the possible synergistic effects of these potential toxicants in low alkalinity waters. American shad *Alosa sapidissima* was included in Hendrey's list of focal species. To date, little information on American shad tolerances to acidic conditions has been reported (Bradford et al. 1968; Klauda and Bender 1987).

This paper describes the results of several laboratory experiments with early life stages of American shad that were conducted between 1985 and 1990. These experiments were secondary to and conducted along with experiments that focused on blueback herring *Alosa aestivalis* (Klauda and Palmer 1987; Klauda et al. 1987). The goal of the American shad experiments was to determine the sensitivity of eggs and larvae to acid and aluminum exposures, use these laboratory results to define lethal and critical effects thresholds for the early life history stages, and then speculate on the effects of pH depressions and aluminum peaks in low alkalinity spawning and nursery areas in Maryland rivers on stock status.

Deriving effects thresholds from laboratory experiments is one approach that can be used to predict the responses of fish populations to changes in surface water acidity (Baker et al. 1987; Huckabee et al. 1989). The underlying rationale for this area of research is to determine if there are any connections among the following three observations:

> — *American shad stocks declined dramatically in Maryland waters of the Chesapeake Bay beginning in the mid to late 1950's*;
> — *Maryland watersheds are receiving significant loadings of acidic deposition*;
> — *Many coastal plain streams and some coastal plain rivers in Maryland are sensitive to acid inputs and experience runoff-induced pH depressions, often accompanied by elevated levels of aluminum.*

Not only have commercial landings declined dramatically in Maryland (Figure 1), but abundance indices for juvenile American shad based on a seine survey (directed at juvenile striped bass *Morone saxatilis*) have also steadily declined since 1960 (Speir 1987; CEC 1989; Anninos et al. 1990). As a response to the depressed stock status, the Maryland Department of Natural Resources issued a moratorium on all fishing for American shad in Chesapeake Bay and tributaries in 1980, a ban that continues to date.

Only two Maryland stocks (Susquehanna River, Potomac River) show any early signs of recovery (Klauda et al. 1991; Richkus et al. 1991; Figure 2). The remnant population of American shad in the Potomac River that declined dramatically during the 1970's (Table 1) is currently at low levels of abundance (Klauda et al. 1991). However, juvenile catches in recent years have increased and may signal the beginning of a recovery trend (Richkus et al. 1991). The most encouraging signs of stock recovery are in the lower Susquehanna River and upper Chesapeake Bay (Klauda et al. 1991; Richkus et al. 1991). This region once had the largest population of spawning American shad in Maryland (Speir 1987) and accounted for a large percentage of the commercial landings until the stock collapsed during the mid 1970's (Table 1).

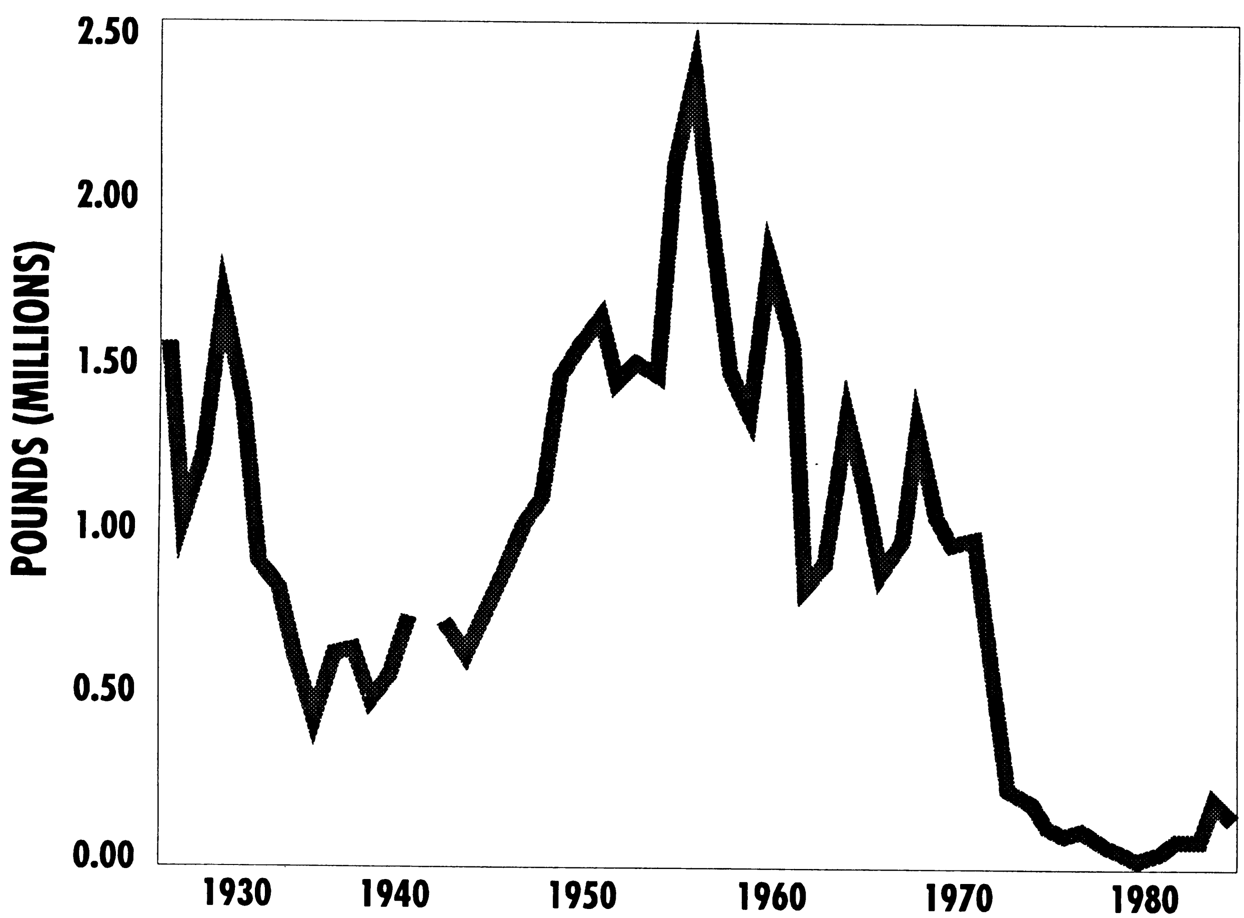

FIGURE 1.—Reported commercial landings of American shad in Maryland between 1929 and 1986 (from Jones et al. 1988). Landings from 1963 through 1986 include the ocean intercept fishery that operates off Ocean City, Maryland.

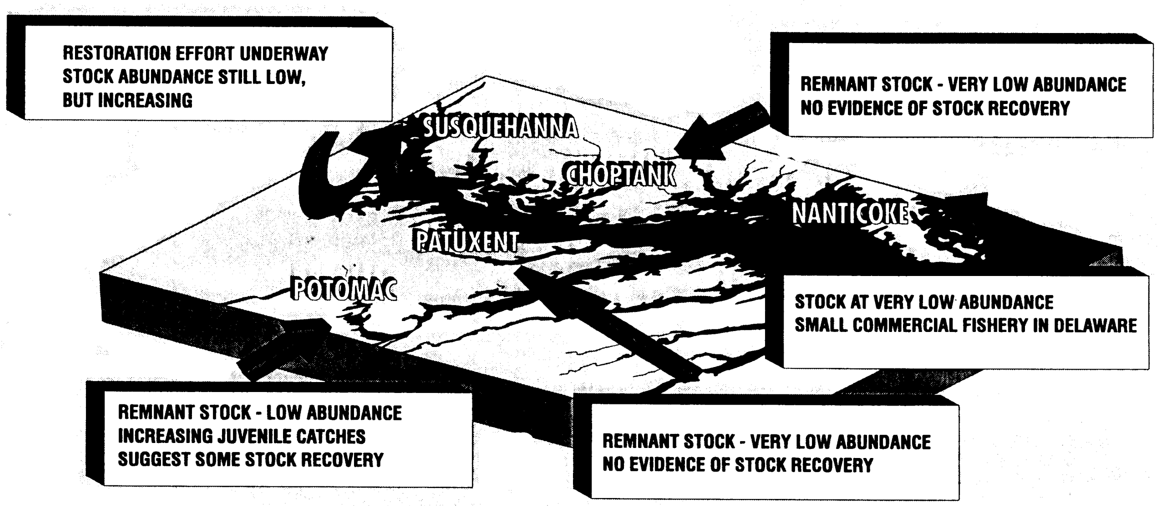

FIGURE 2.—Current status of American shad stocks in five Maryland rivers (from Klauda et al. 1991 and Richkus et al. 1991).

TABLE 1.— Reported commercial landings of American shad in Maryland by selected area or river system. Percentages of total Maryland landings from each year are given in parentheses.

	Commercial landings in pounds by year							
Area or river	1896[a]	1944[b]	1945[b]	1951[c]	1952[c]	1960[a]	1969[e]	1975[e]
Upper Chesapeake Bay and lower Susquehanna River	1,435,366 (26)	153,597 (22)	157,371 (26)	609,144 (39)	589,405 (36)	952,203 (71)	106,656 (9)	15,200 (16)
Patuxent River	188,262 (3)	1,312 (<1)	849 (<1)	1,441 (<1)	3,427 (<1)	797 (<1)	NR[f]	NR[f]
Potomac River	838,704 (3)	48,065 (7)	50,318 (8)	66,518 (4)	147,391 (9)	32,276 (2)	NR[f]	NR[f]
Nanticoke River	589,160 (11)	33,123 (5)	16,606 (3)	29,110 (2)	56,370 (3)	94,792 (7)	NR[f]	6,900
Choptank River	1,224,897 (22)	26,465 (4)	30,613 (5)	16,750 (1)	41,462 (3)	11,130 (1)	60,300 (5)	NR[f]
Maryland total[d]	5,541,499	709,070	606,494	1,553,134	1,634,476	1,335,953	1,185,067	95,000

[a]From Walburg and Nichols (1967).
[b]From Hammer et al. (1948).
[c]From Hensel and Tiller (1954).
[d]Includes areas other than those included in this table.
[e]From Krauthamer and Richkus (1987)
[f]NR = not reported; landings either represent less than 5% of the total landings or the area/river is not reported separately.

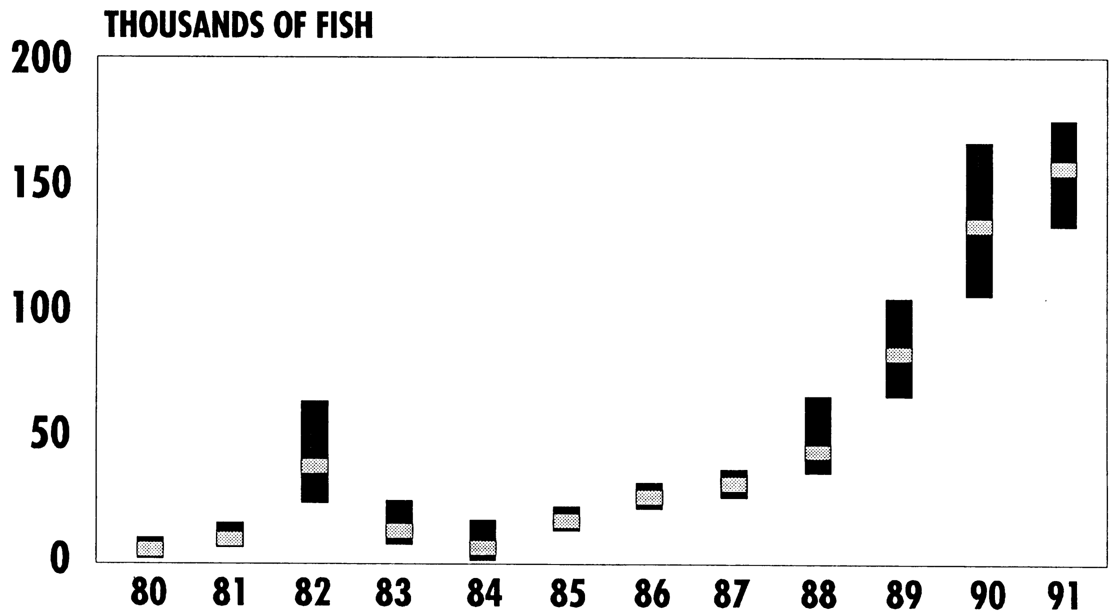

FIGURE 3.—Trend in mark-recapture population estimates of adult American shad in upper Chesapeake Bay (mean±95% confidence interval) based on Chapman's modification to the Petersen method (from Krantz et al. 1992).

stock collapsed during the mid 1970's (Table 1).

In spring 1991, the Petersen population estimate of adult American shad in this region was about 141,000 fish, a 14% increase over the 1990 estimate but a substantial increase over the 1981 estimate (Krantz et al. 1992, Figure 3). Other positive signs of some stock recovery in this region were increases in the percentage of repeat spawners (sexes combined) from 10.4% in 1989 to 19.4% in 1991, and increases in the numbers of virgin females from 95 in 1988 to 301 in 1991. Nevertheless, Krantz et al. (1992) cautioned that these numbers are still low when compared to historical data, and urged that conservative management practices remain intact to allow for continued stock rebuilding. This strong positive trend did not continue into spring 1992 and 1993 when the population estimates of adult American shad were 105,255 and 47,563 fish (SRAFRC 1994). At present, there is no explanation for these recent declines.

In spite of declines in abundance in 1992 and 1993, the American shad population in the lower Susquehanna River/upper Chesapeake Bay is apparently benefiting from a combination of the continuing moratorium on fishing, operations of two fish bypass facilities at Conowingo Dam, and intensive transport and stocking efforts (SRAFRC 1990). The impetus for this restoration program can be traced to a 1970 agreement among several utilities (Philadelphia Electric Company, Susquehanna Electric Company, Pennsylvania Power and Light Company, Metropolitan Edison Company, Safe Harbor Water Power Corporation), the States of Maryland and New York, the Commonwealth of Pennsylvania, and the U.S. Department of the Interior (Kotkas and Robbins 1976). This agreement called for the implementation of a five-year program "for restoration of the American shad to the Susquehanna River" that was extended and continues to date.

By comparison, American shad stocks in two Eastern Shore Maryland rivers (Nanticoke and Choptank) and the Patuxent River on the Western Shore are still at low levels of abundance and show no signs of recovery (Klauda et al. 1991; Richkus et al. 1991; Krantz et al. 1992). In 1896, American shad landings in the Nanticoke River ranked fourth among Maryland rivers, and contributed about 11% of the total landings (Table 1). The reported catch in the Nanticoke was 812,417 lbs, with 223,257 lbs landed in Delaware, 141,000 lbs landed in the Maryland portion of Marshyhope Creek (a major tributary) and 448,160 lbs landed in the Maryland portion of the Nanticoke River (Walburg and Nichols 1967). But, by 1960, the Nanticoke River stock contributed only 7% of Maryland's total American shad commercial landings of only 95,000 lbs (Table 1). This percentage contribution increased to 18%, 19% and 28% in 1977, 1978, and 1979; however, the total pounds of shad landed in the Nanticoke River steadily decreased (Krauthaumer and

Since the 1980 moratorium in Maryland, the only fishery for American shad that still exists in a Maryland tributary to the Chesapeake Bay occurs in the Delaware portion of the Nanticoke River near Woodland Ferry. Annual reported landings between 1976 and 1991 averaged 1,984 lbs (Figure 4). Peak landings during this period occurred in 1981 (3,800 lbs) and 1991 (3,302 lbs). Krantz et al. (1992) estimated an annual mortality rate for American shad in the Nanticoke River (1988-1991) of 77.4% (95% confidence interval ± 21.8%). They concluded that the Delaware commercial fishery for American shad in the Nanticoke River may be having an adverse effect on the remnant stock and could be slowing its recovery.

Reported commercial landings of American shad in the Choptank River were over 1.2 million lbs in 1896 and contributed 22% of Maryland's total landings (Table 1). Since 1930, annual landings have declined and ranged between 20,000 and 50,000 lbs until 1977 when they declined further to nearly zero (Richkus et al. 1991). Major peaks in reported landings during this time period occurred in 1955 (about 120,000 lbs), 1968 (about 70,000 lbs) and 1969 (about 60,000 lbs). From 1944 to 1970, the Choptank River's contribution of American shad to total commercial landings in Maryland ranged from only 1 to 5% (Table 1; Krauthamer and Richkus 1987). The current remnant stock is at very low levels of abundance and shows no signs of recovery (Klauda et al. 1991).

Commercial landings of American shad in the Patuxent River were never large and contributed only modestly to total Maryland landings (Table 1). Even in 1896, when the reported commercial harvest of American shad in Maryland was about 5.5 million lbs, Patuxent River landings were less than 0.2 million lbs, only 3% of the Maryland total. In all but four years of the recent data record (since 1930), annual landings were less than 5,000 lbs (Richkus et al. 1991). The remnant stock is currently at a very low level of abundance and may still be declining (Klauda et al. 1991).

Habitat acidification associated with acid deposition appears to be an ecological problem in some tributaries of the Chesapeake Bay that drain the Coastal Plain physiographic province (Janicki and Cummins 1983; Hall et al. 1985). Maryland receives some of the highest loadings of sulfate and nitrate in the United States (Figures 5 and 6), with two-thirds of the acid deposition originating from sources outside the state (PPRP 1992). In 1990,

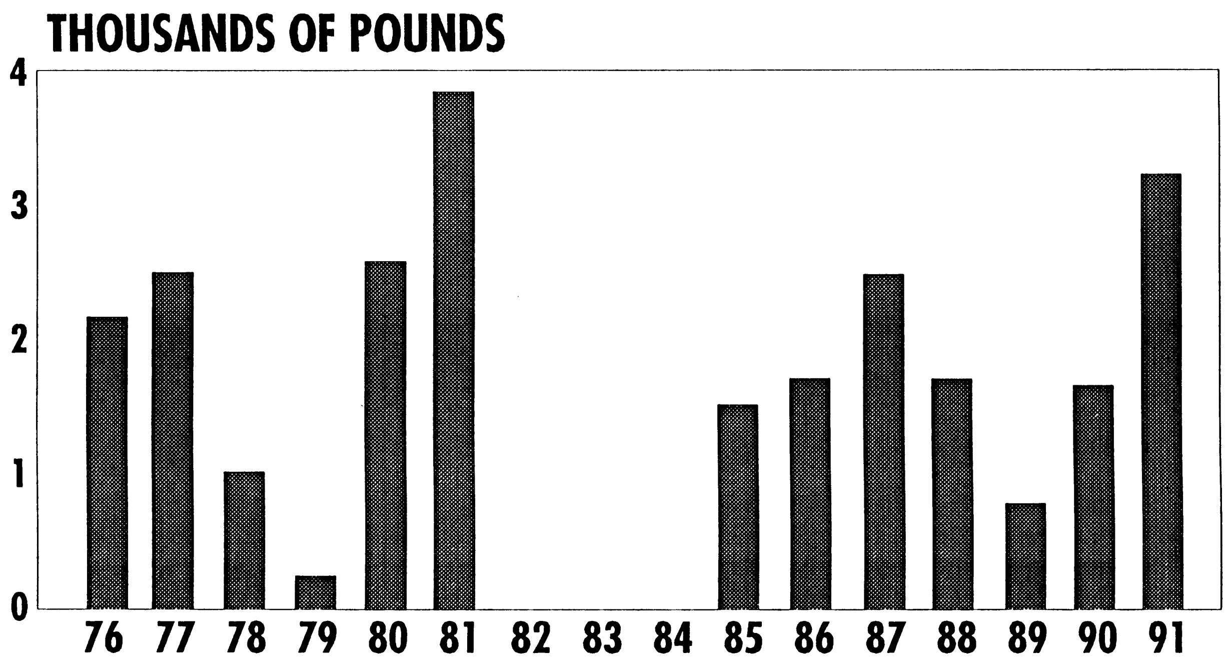

FIGURE 4.—Reported commercial landings of American shad in the Delaware portion of the Nanticoke River between 1976 and 1991. Data were not available for 1982-1984.

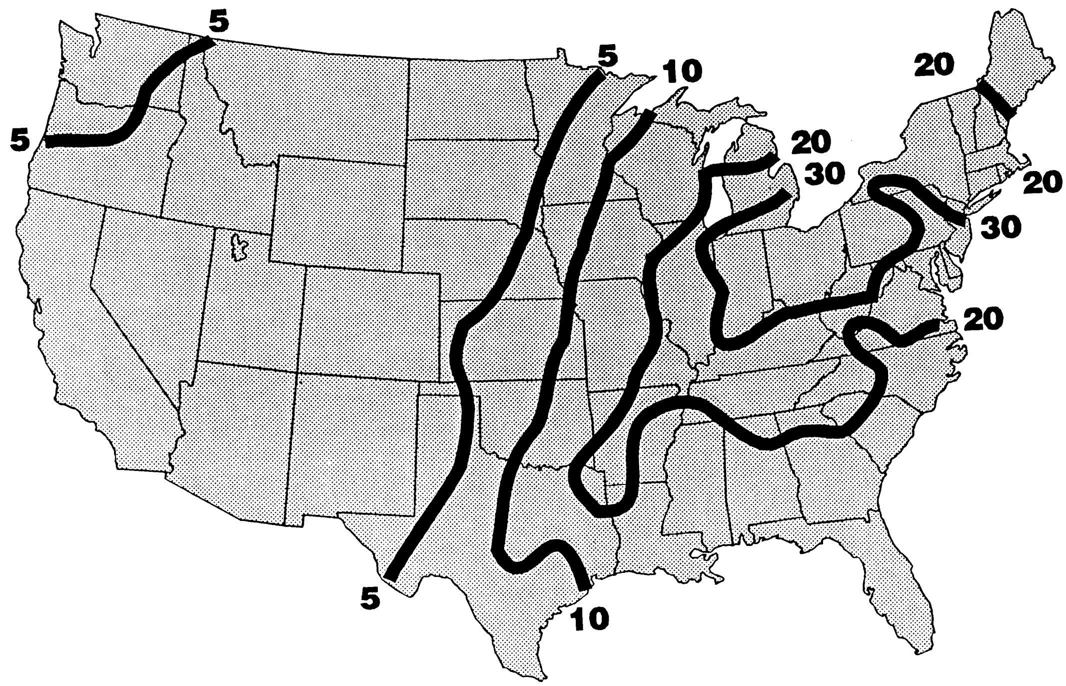

FIGURE 5.—Estimated sulfate ion wet deposition (kg/hectare) in Maryland compared to the rest of the United States in 1990 (from NADP/NTN 1991).

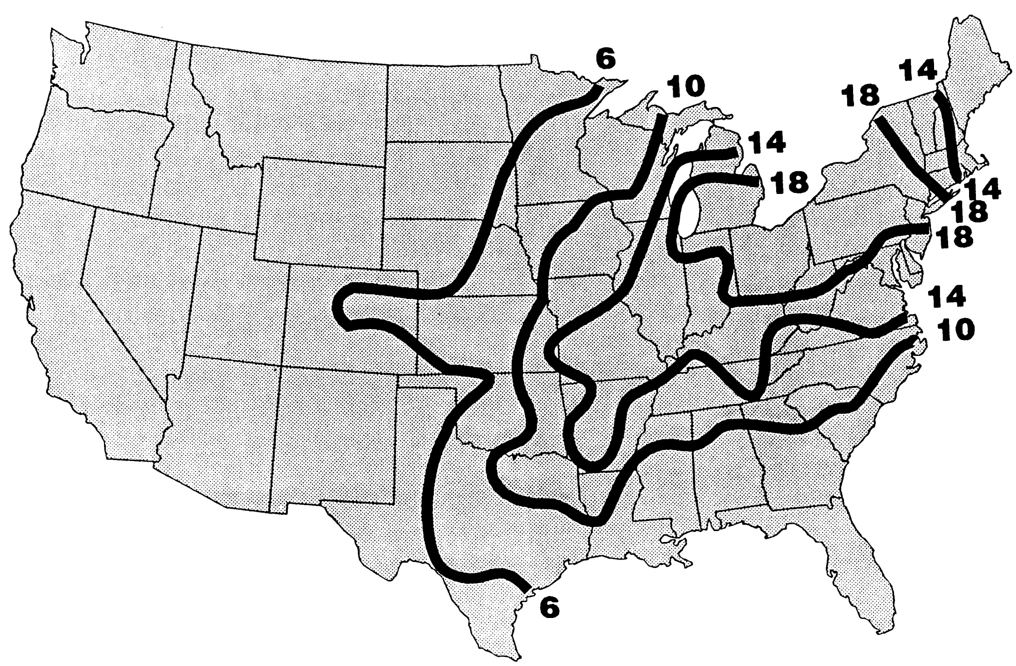

FIGURE 6.—Estimated nitrate ion wet deposition (kg/hectare) in Maryland compared to the rest of the United States in 1990 (from NADP/NTN 1991).

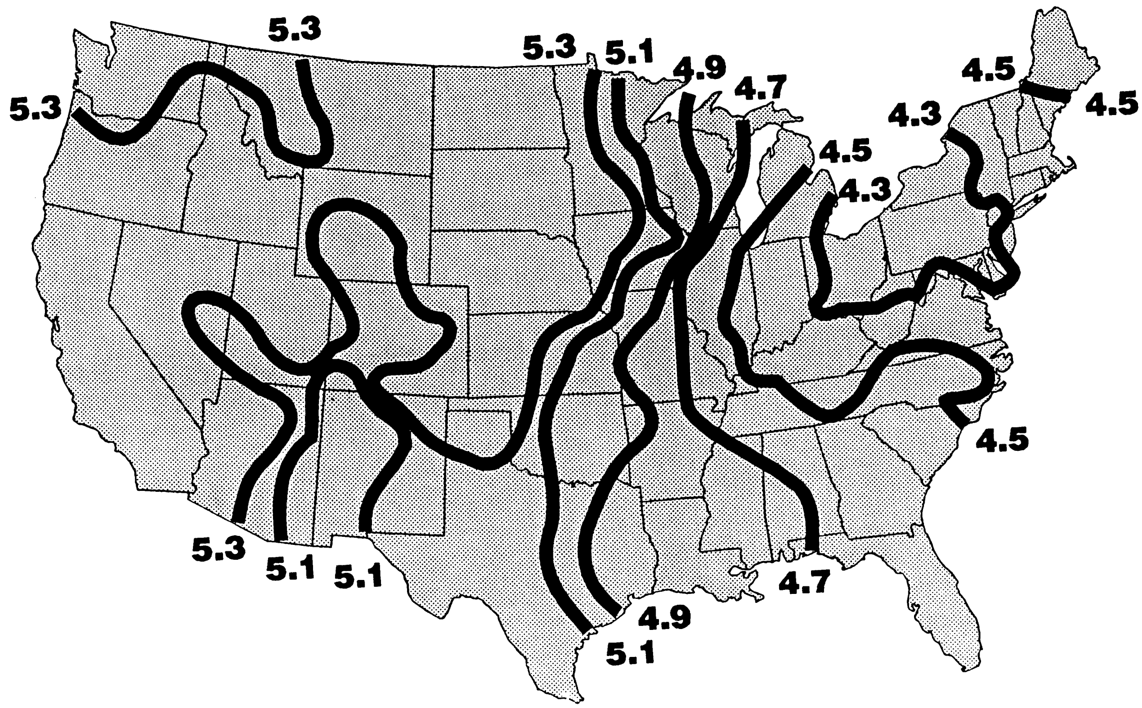

FIGURE 7.—Annual precipitation volume-weighted mean hydrogen ion deposition (expressed as pH) in Maryland compared to the rest of United States in 1990 (from NAD/NTN 1991).

Maryland received 25 kg/hectare of sulfate in the form of wet deposition (NADP/NTN 1991). Wet deposition loadings of nitrate ranged from 16 to 18 kg/hectare. Mean annual pH of precipitation collected in Maryland during 1990 was 4.3 (Figure 7), almost 10 fold more acidic than normal precipitation. Minimum and maximum precipitation pH values recorded at monitoring stations in Maryland in 1990 were 3.5 and 6.5.

The coastal plain region of Maryland is underlain by thick layers of unconsolidated sand and gravel, silty sand, marl and shell beds superimposed upon buried rocks of the Piedmont province (Otton 1970). The thickness of coastal plain sediments preclude interaction between acid deposition and bedrock. Soil pH and base saturation characteristics of the soils are low (Figures 8 and 9).

The relatively low alkalinity (or acid neutralizing capacity) values in many coastal plain Maryland streams and in some of the Eastern Shore Maryland rivers such as the Choptank and Nanticoke (Tables 2 to 4) are characteristic of acid-sensitive surface waters (Correll et al. 1984, 1987; Janicki and Greening 1987; Knapp et al. 1988a). These tributaries can experience temporary pH depressions (or pulses) and become periodically toxic to the early life stages of several migratory fish species (Klauda 1989; Hall et al. 1993). Such pulses or episodes are characterized by temporary depressions (a few hours to a few days in duration) of pH (from circumneutral to 4.5-6.0) and alkalinity (from 10 or 15 to less than 1 mg/L as $CaCO_3$). Storm-induced pH depressions and temporary reductions in buffering capacity may also be accompanied by substantial increases in aluminum concentration to peaks of 4,100 g/L for total aluminum, almost 800 g/L for the dissolved fraction and about 160 g/L for the toxic inorganic monomeric fraction (Table 5).

A baseflow alkalinity value of about 10 mg/L (as $CaCO_3$) corresponds to an acid neutralizing capacity (ANC) of about 200 eq/L, a generally accepted threshold for surface water sensitivity to acid inputs (Knapp et al. 1988a). Gerritsen et al. (1989) reported that coastal plain Maryland streams and rivers with baseflow ANC less than 300 eq/L (about 15 mg/L of alkalinity as $CaCO_3$) are also at risk to pH depressions that may be harmful to the larvae of sensitive migratory fish species such as blueback herring, alewife *Alosa pseudoharengus*, white perch *Morone americana*, and striped bass. The lower the ANC in a stream or lake below 200 eq/L, the lower the buffering capability and the greater the sensitivity to acid inputs. A water body is defined to be acidic when its ANC falls below 0.

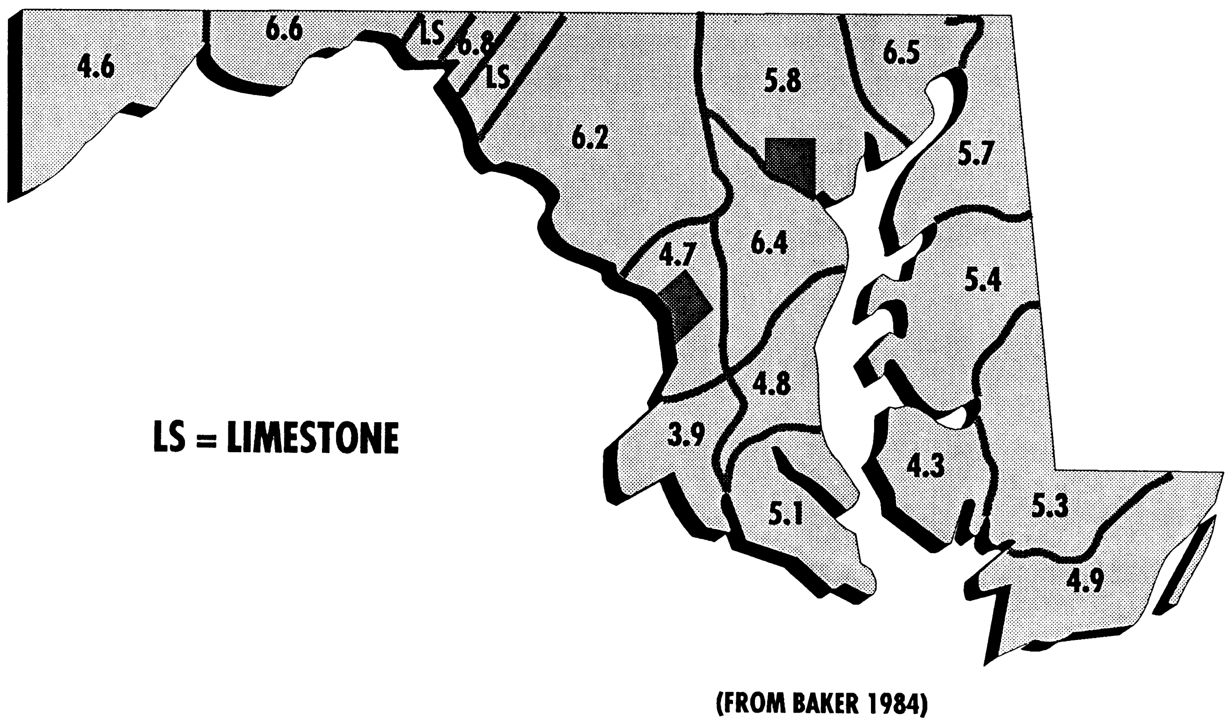

FIGURE 8.—Mean soil pH for various soil associations in Maryland (from Baker 1984).

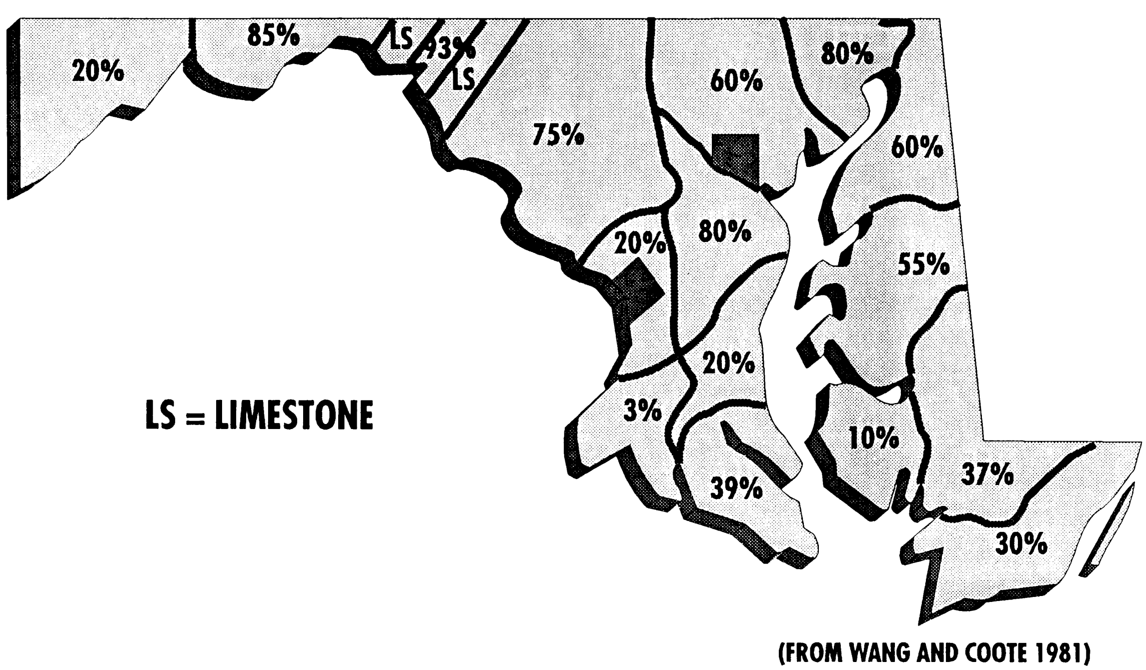

FIGURE 9.—Percent base saturation of various soil associations in Maryland (from Wang and Coote 1981).

TABLE 2.— Selected water quality data compiled to characterize the acid sensitivity of the Choptank River near Greensboro, MD (96 km upstream from river mouth), and in striped bass spawning areas. NC = not calculated and NR = not reported.

Data source	Time period	Statistic	pH	Specific conductance (μS/cm)	Total hardness as $CaCO_3$ (mg/L)	Alkalinity (mg/L)	Dissolved Calcium (mg/L)	Dissolved Aluminum (μg/L)	Dissolved organic carbon (mg/L)
USGS 1975	October 1971 to September 1972	Minimum	6.3	64	19	6	4.8	<10	NR
		Mean	6.8	105	31	15	8.1	100	NR
		Median	6.7	107	30	13	8.0	100	NR
		Maximum	7.5	130	43	26	12.0	200	NR
USGS 1980	October 1978 to September 1979	Minimum	6.7	64	21	6	5.4	NR	4.7
		Mean	7.2	134	33	15	8.8	NR	7.4
		Median	7.3	120	35	16	9.4	NR	6.9
		Maximum	7.7	260	50	27	14.0	NR	11.0
James et al. 1984	October 1982 to September 1983	Minimum	5.9	83	18	7	4.6	<10	NR
		Mean	6.8	144	31	13	8.2	135	NR
		Median	7.0	159	23	9	6.1	200	NR
		Maximum	7.2	175	51	22	14.0	200	NR
Hall 1987	April 1984[a]	Single Grab Sample	6.3	130	34	NR	NR	NR	NR
Hall 1987	April, May and June 1984	Minimum	5.6	NR	NR	NR	NR	NR	NR
		Mean	6.6	NR	NR	NR	NR	NR	NR
		Median	6.7	NR	NR	NR	NR	NR	NR
		Maximum	7.6	NR	NR	NR	NR	NR	NR
Hall 1987	April 1985[a]	Single Grab Sample	8.6	220	40	27	NR	69	NR
James et al. 1988	October 1986 to September 1987	Minimum	5.0	73	25	7	6.2	<10	2.9[b]
		Mean	6.7	139	41	17	10.8	105	6.3[b]
		Median	6.7	130	39	15	10.2	40	5.7[b]
		Maximum	7.6	213	55	41	15.0	440	12.0[b]
Hall et al. 1988a	April 1987[a]	Minimum	6.9	100	36	16	NR	5	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	NR	NR	NR	NR	NR	NR	NR
		Maximum	7.2	195	48	19	NR	220	NR
Hall et al. 1991	May 1989[a]	Single Grab Sample	6.3	130	34	NR	NR	NR	NR
James et al. 1992	October 1990 to September 1991	Minimum	5.5	56	37	9	9.6	<10	5.2
		Mean	6.0	122	42	20	11.1	52	NC(n=1)
		Median	6.0	126	41	21	11.0	30	NC(n=1)
		Maximum	6.9	169	52	30	14.0	190	5.2

[a]Sample collected off Rt. 404 at Martinek State Park near Denton, MD.
[b]Total organic carbon (mg/L)

The Choptank and Nanticoke are two Eastern Shore rivers that possess limited buffering capacity and are vulnerable to acidic deposition (Tables 2 to 4). In the Choptank River, pH depressions to less than 6.5 were relatively common between 1965 and 1984 (Janicki et al. 1986). Minimum pH values less than 6.0 were observed in 1969, 1974, 1978, and 1980. By comparison, few if any such pH depressions were observed in the data sets analyzed by Janicki et al. (1986) for the Potomac River, a major Western Shore tributary to the Chesapeake Bay. Alkalinity levels in the Potomac, Patuxent and Susquehanna rivers (Tables 6 to 8) are typically higher than in most Eastern Shore rivers. Higher alkalinities will ensure better buffering of acidic inputs, lower frequencies of pH depressions below 6.5 or 6.0, and fewer episodes of increased aluminum concentrations that are potentially toxic to the early life stages of sensitive fish species (Table 5). Therefore, because of their alkalinity values, the Potomac, Patuxent, and Susquehanna rivers are not particularly sensitive to acidic deposition.

Klauda and Bender (1987) concluded that "to date ...no direct link between acidic deposition, habitat acidification, and fish mortality has been established for any Maryland watershed." This conclusion is still accurate for migratory fish species that spawn in Maryland rivers and streams. The

TABLE 3.— Water quality data reported by Uphoff (1989, 1992) for the Choptank River, MD, between km 56 and 79 from the river mouth, April to mid-June, 1983 - 1988. NR = not reported.

Year	Statistic	pH	Specific conductance (μS/cm)	Total hardness as $CaCO_3$ (mg/L)	Alkalinity (mg/L)
1983	Minimum	6.2	60	24	10.0
	Mean	6.7	190	50	17.4
	Maximum	7.5	2300	139	21.1
1984	Minimum	6.4	120	34	16.2
	Mean	6.9	290	69	21.8
	Maximum	8.0	1610	182	32.7
1985	Minimum	6.7	690	122	18.0
	Mean	7.1	3320	473	29.2
	Maximum	7.9	7200	960	37.0
1986	Minimum	6.6	137	NR	NR
	Mean	7.2	1353	NR	NR
	Maximum	9.2	7200	NR	NR
1987	Minimum	6.4	157	NR	20.0
	Mean	6.7	874	NR	26.5
	Maximum	7.6	3460	NR	35.0
1988	Minimum	6.3	268	NR	24.0
	Mean	6.7	1247	NR	33.3
	Maximum	8.7	8270	NR	42.0

laboratory test results described in this paper take a logical first step in the search for possible connections among habitat acidification, mortality of American shad early life stages, stock status, and rate of stock recovery.

Objectives

The laboratory experiments described in this paper had four objectives: 1) expose American shad eggs and larvae to a range of acid and aluminum pulses of several durations; 2) measure sensitivity of these early life stages to the range of acid and aluminum pulses; 3) define lethal and critical conditions (pulse magnitude and duration) for exposure of the early life stages to acid and aluminum; and 4) compare sensitivity of American shad and fathead minnow *Pimephales promelas* larvae to acid and aluminum pulses.

The laboratory study results were used to address these four questions: 1) are American shad eggs and larvae sensitive to acid and aluminum exposures that reflect periodic environmental conditions observed in some Maryland spawning rivers; 2) what are the lethal and critical acid and aluminum conditions for American shad eggs and larvae; 3) could acid deposition and habitat acidification have contributed to American shad stock declines in Maryland; and 4) is habitat acidification slowing the recovery of some American shad stocks in Maryland?

Methods

General Procedures

Between 1985 and 1990, 11 laboratory experiments were conducted to measure the sensitivity of American shad eggs and larvae to acid and aluminum pulses (Table 9). These shad experiments were secondary to a series of experiments with blueback herring eggs and larvae (reported in Klauda and Palmer 1987; Klauda et al. 1987) and could be carried out only when American shad eggs and larvae and test tank space were available. Therefore, the 11 experiments with American shad should be viewed as a collection of individual experiments with partial linkage to an overall experimental design. In spite of this limitation, the paucity of data in the literature on the sensitivity of American shad eggs and larvae to acid and aluminum exposures justifies the presentation of the laboratory results reported in this paper.

TABLE 4.— Selected water quality data compiled to characterize the acid sensitivity of the Nanticoke River, near Sharptown, MD (44 km upstream from river mouth), near Woodland Ferry, DE (54 km upstream from river mouth), at Maryland-Delaware state line (48 km upstream from river mouth), and in striped bass spawning areas. NR = not reported and NC = not calculated (n = 1).

Data source	Location and time period	Statistic	pH	Specific conductance (µS/cm)	Total hardness as $CaCO_3$ (mg/L)	Alkalinity (mg/L)	Dissolved Calcium (mg/L)	Dissolved Aluminum (µg/L)	Dissolved organic carbon (mg/L)
USGS 1975	Sharptown Bridge, MD October 1971 to September 1972	Minimum	6.1	75	23	20	4.6	<10	NR
		Mean	6.6	107	25	22	NC	100	NR
		Median	6.6	85	25	22	NC	100	NR
		Maximum	7.2	200	26	23	4.6	200	NR
Delaware DNR/EC 1976	Sharptown Bridge, MD October 1974 to September 1975	Minimum	6.7	NR	20	10	NR	NR	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	7.1	NR	25	17	NR	NR	NR
		Maximum	7.5	NR	78	26	NR	NR	NR
Delaware DNR/EC 1976	Woodland Ferry, DE October 1974 to September 1975	Minimum	6.7	NR	10	10	NR	NR	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	7.1	NR	20	13	NR	NR	NR
		Maximum	7.7	NR	25	26	NR	NR	NR
Delaware DNR/EC 1980	Sharptown Bridge, MD October 1978 to September 1979	Minimum	6.3	NR	0	9	NR	NR	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	7.3	NR	32	13	NR	NR	NR
		Maximum	7.8	NR	37	16	NR	NR	NR
Delaware DNR/EC 1980	Woodland Ferry, DE October 1978 to September 1979	Minimum	6.6	NR	0	8	NR	NR	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	7.2	NR	31	14	NR	NR	NR
		Maximum	7.4	NR	36	15	NR	NR	NR
Hall 1984, Hall et al. 1985	April 1984[a]	Minimum	6.1	8.5	23	NR	NR	NR	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	NR	NR	NR	NR	NR	NR	NR
		Maximum	6.8	105	64	NR	NR	NR	NR
Hall 1987	April, May, June 1984[b]	Minimum	6.0	NR	NR	NR	NR	NR	NR
		Mean	6.7	NR	NR	NR	NR	NR	NR
		Median	6.7	NR	NR	NR	NR	NR	NR
		Maximum	8.2	NR	NR	NR	NR	NR	NR
Hall 1987	April 1984[b]	Single Grab Sample	6.1	100	29	NR	NR	NR	NR
Hall 1987	April 1985[b]	Single Grab Sample	7.0	2400[c]	282[c]	24	NR	120	NR
Delaware DNR/EC 1990	State Line, Buoy 45 June 1988	Minimum	7.4	NR	46	22	NR	NR	NR
		Mean	NC	NR	NC	NC	NR	NR	NR
		Median	NC	NR	NC	NC	NR	NR	NR
		Maximum	7.4	NR	46	22	NR	NR	NR
Delaware DNR/EC 1990	Woodland Ferry, DE September 1987 to September 1989	Minimum	5.8	92	NR	10	NR	NR	NR
		Mean	7.1	104	NR	18	NR	NR	NR
		Median	NR	NR	NR	NR	NR	NR	NR
		Maximum	7.9	113	NR	29	NR	NR	NR
Hall et al. 1991	April 1989[b]	Single Grab Sample	7.2	150	30	15	NR	110	NR
Delaware DNR/EC 1992	State Line, Buoy 45 September 1990 to August 1991	Minimum	7.1	104	28	12	NR	NR	6.0[d]
		Mean	7.4	178	43	20	NR	NR	7.7[d]
		Median	NR	NR	NR	NR	NR	NR	NR
		Maximum	7.8	380	62	28	NR	NR	11.0[d]
Delaware DNR/EC 1992	Woodland Ferry, DE September 1989 to August 1991	Minimum	6.8	96	26	10	NR	NR	5.0[d]
		Mean	7.3	129	46	17	NR	NR	7.0[d]
		Median	NR	NR	NR	NR	NR	NR	NR
		Maximum	7.8	212	74	26	NR	NR	9.4[d]

[a]Samples collected from stations at Riverton, MD (36 km from river mouth), at Vienna, MD (32 km from river mouth) and just below confluence with Mill Creek (29 km from river mouth).

TABLE 5.— Aluminum concentrations reported by various investigators in American shad spawning rivers and areas in Maryland. TD = total dissolved (0.4 m filter); T = total unfiltered; TM = total monomeric (0.1 m filter + MIBK); IM = inorganic monomeric (pyrocatechol violet); NR = not reported; NA = not applicable (single grab sample).

		Aluminum concentration (and form) in μg/l		
River or area	Year and location	Range	Median	Data source
Choptank	1971-72	<10 to 200 (TD)	100 (TD)	USGS 1975
	1982-83	<10 to 200 (TD)	200 (TD)	James et al. 1984
	1985[a]	69 (TD), 16 (TM)	NA	Hall et al. 1986
	1986-87	<10 to 440 (TD)	NA	Hall 1985
	1986[a]	160 (TD), 77 (TM)	40 (TD)	James et al. 1988
	1987	< 5 to 39 (TD)	NR	Hall et al. 1988a
	1987	60 to 150 (TM)	NR	Hall et al. 1988a
	1988[a]	60 (TD)	NA	Hall et al. 1988b
	1989[a]	156 (TD), 112 (TM)	NA	Hall et al. 1991
	1989	4 to 20 (TM)	7 (TM)	Hall et al. 1991
Nanticoke	1972	<10 to 200 (TD)	100 (TD)	USGS 1975
	1984	480 to 4100 (T)	1000 (T)	Hall 1984
	1984	54 to 459 (TD)[b]	112 (TD)[b]	Hall 1984
	1984	39 to 181 (TD)	NR	Mehrle et al. 1986
	1985	18 to 35 (TD)	NR	Mehrle et al. 1986
	1985[a]	120 (TD), 2 (TM)	NA	Hall 1985
	1986	42 to 65 (TD)	NR	Mehrle et al. 1986
	1986[a]	60 (TD), 55 (TM)	NA	Hall et al. 1986
	1988[a]	70 (TD)	NA	Hall et al. 1988b
	1989[a]	110 (TD), 72 (TM)	NA	Hall et al. 1991
	1992[c]	110, 130, 160 (IM)	NR	Secor et al. 1993
Potomac	1978-79	30 to 80 (TD)	40 (TD)	USGS 1980
	1982-83	<10 to 70 (TD)	30 (TD)	James et al. 1984
	1985[a]	59 (TD), 3 (TM)	NA	Hall 1985
	1986	<40 to 240 (TD)	NR	Hall et al. 1987, Hall 1988
	1986	19 to 90 (TM)	NR	Hall et al. 1987, Hall 1988
	1986[a]	90 (TD), 32 (TM)	NA	Hall et al. 1986
	1986-87	<10 to 80 (TD)	30 (TD)	James et al. 1988
	1988[a]	<60 (TD)	NA	Hall et al. 1988b
	1989[a]	14 (TD)	NA	Hall et al. 1991
	1990	14 to 740 (TD)	77 (TD)	Hall et al. 1992
	1990-91	<10 to 80 (TD)	20 (TD)	James et al. 1992
Patuxent	1982-83	<10 to 40 (TD)	23 (TD)	James et al. 1984
	1985[a]	19 (TD), <2 (TM)	NA	Hall 1985
	1986[a]	240 (TD), 112 (TM)	NA	Hall et al. 1986
	1986-87	<10 to 150 (TD)	40 (TD)	James et al. 1988
	1988[a]	150 (TD)	NA	Hall et al. 1988b
	1989[a]	36 (TD), 10 (TM)	NA	Hall et al. 1991
	1990-91	<10 to 190 (TD)	20 (TD)	James et al. 1992
Susquehanna and upper Chesapeake Bay	1978-79	<10 to 150 (TD)	40 (TD)	USGS 1980
	1982-83	<10 to 50 (TD)	15 (TD)	James et al. 1984
	1986-87	<10 to 100 (TD)	30 (TD)	James et al. 1988
	1989	15 to 367 (TD)	30 (TD)	Hall et al. 1991
	1989	< 2 to 52 (TM)	18 (TM)	Hall et al. 1991
	1990	22 to 780 (TD)	258 (TD)	Hall et al. 1992
	1990-91	<10 to 190 (TD)	20 (TD)	James et al. 1992

[a]Single grab sample collected during the spring. Mean ratios of TM/TD were calculated as: 0.48 (Choptank), 0.53 (Nanticoke), 0.27 (Potomac), 0.29 (Patuxent), and 0.33 (Susquehanna/upper Bay) from Hall 1985, Hall et al. 1986, Hall et al. 1991.
[b]TD form was estimated from mean ratio of TD/T = 0.11 (Hall et al. 1985).
[c]From grab samples collected on 1 May 1992 at Sharptown, MD (42 km from river mouth), in lower portion of Marshyhope Creek (2 km from creek mouth), and at Riverton, MD (36 km from river mouth).

Two experiments were conducted with fertilized eggs, six experiments with prefeeding yolk-sac larvae, and three experiments with feeding post yolk-sac larvae. Egg batches were obtained from the Van Dyke Anadromous Fish Culture Station operated by the Pennsylvania Fish and Boat Commission and located on the Juniata River near Thompsontown, Pennsylvania. Fertilized eggs were transported to our laboratory in Shady Side, Maryland, and incubated in 7.0-L hatching jars with a water flow rate of 1 to 2 L/min that gently rolled the eggs. Larvae were reared in flow-through aquaria and fed brine shrimp nauplii (*Artemia* spp.) several times per day beginning at about 5 d post-hatch.

Fertilized eggs were incubated, larvae were reared, and acid and aluminum exposure tests were conducted in reconstituted well water. Source water came from a nonchlorinated and uncontaminated deep well. Chemical composition of the raw well water was reported in Klauda and Palmer (1987) and Klauda et al. (1987). Well water was demineralized to a specific conductance of 3 to 6 S/cm with either a Culligan Anion/Cation Duabed system or a Zenon Reverse Osmosis system, and reconstituted to test strength by adding sufficient raw well water to achieve a total hardness between 20 and 30 mg/L (as $CaCO_3$). Concentrations of test water analytes (Table 10) were representative of those Maryland streams and rivers with limited buffering capacity

TABLE 6.— Selected water quality data compiled to characterize the acid sensitivity of the Potomac River at Chain Bridge near Washington, DC (157 km upstream from river mouth), and in striped bass spawning areas. NR = not reported.

Data source	Time period and location	Statistic	pH	Specific conductance (μS/cm)	Total hardness as $CaCO_3$ (mg/L)	Alkalinity (mg/L)	Dissolved Ca (mg/L)	Dissolved Al (μg/L)	Dissolved organic carbon (mg/L)
USGS 1975	October 1971 to September 1972[a]	Minimum	7.1	143	58	51	19.0	NR	NR
		Mean	7.6	251	106	87	31.4	NR	NR
		Median	7.6	232	105	83	31.0	NR	NR
		Maximum	8.2	392	170	151	50.0	NR	NR
USGS 1980	October 1978 to September 1979	Minimum	7.7	135	43	29	13.0	30	2.1
		Mean	8.2	242	96	68	28.2	43	5.0
		Median	8.2	225	89	67	27.0	40	5.3
		Maximum	8.7	450	200	140	58.0	80	8.1
James et al. 1984	October 1982 to September 1983	Minimum	7.7	86	73	50	21.0	<10	NR
		Mean	8.0	294	115	80	32.8	33	NR
		Median	8.1	295	114	79	33.0	30	NR
		Maximum	8.3	430	160	108	43.0	70	NR
James et al. 1988	October 1986 to September 1987	Minimum	7.5	224	80	54	23.0	<10	3.4
		Mean	8.0	297	118	82	34.2	34	5.9
		Median	7.9	275	110	78	31.0	30	4.6
		Maximum	8.4	492	190	120	56.0	80	11.0
Hall 1987	May 1984[b]	Single Grab Sample	8.2	190	60	NR	NR	NR	NR
Hall et al. 1987; Hall 1988	April 1986[c]	Minimum	7.1	140	72	40	NR	<40	NR
		Mean	NR	NR	NR	NR	NR	NR	NR
		Median	NR	NR	NR	NR	NR	NR	NR
		Maximum	8.7	280	116	105	NR	240	NR
James et al. 1992	October 1990 to September 1991	Minimum	6.6	195	82	56	24.0	<10	2.5[d]
		Mean	7.7	289	119	84	33.2	26	4.3[d]
		Median	7.4	267	115	78	33.0	20	3.3[d]
		Maximum	8.5	363	150	113	40.0	80	13.0[d]
Hall et al. 1991	May 1989[b]	Single Grab Sample	7.9	220	88	55	NR	14	NR
Hall et al. 1992	April-May 1990[e]	Minimum	7.2	173	78	40	NR	14	NR
		Mean	7.6	187	88	59	NR	167	NR
		Median	7.7	185	88	60	NR	80	NR
		Maximum	8.0	208	116	75	NR	740	NR

[a]at Point of Rocks, MD.
[b]Sample collected about 200 m upstream from Rt. 301 bridge (78 km from river mouth).
[c]Samples collected at three stations between Cherry Hill and Widewater, VA (123-140 km from river mouth).
[d]Total organic carbon (mg/L).
[e]Samples collected at three stations off Quantico, VA (133 km from river mouth).

TABLE 7.— Selected water quality data compiled to characterize the acid sensitivity of the Patuxent River near Bowie, MD (96 km upstream from river mouth), and in striped bass spawning areas. NR = not reported.

Data source	Time period and location	Statistic	pH	Specific conductance (µS/cm)	Total hardness as $CaCO_3$ (mg/L)	Alkalinity (mg/L)	Dissolved Ca (mg/L)	Dissolved Al (µg/L)	Dissolved organic carbon (mg/L)
USGS 1980	October 1978 to September 1979	Minimum	7.1	105	29	13	8.1	NR	4.8
		Mean	7.5	186	45	25	12.6	NR	4.9
		Median	7.4	183	48	25	13.5	NR	4.8
		Maximum	7.7	255	54	36	16.0	NR	5.1
James et al. 1984	October 1982 to September 1983	Minimum	7.0	139	38	21	10.0	<10	NR
		Mean	7.2	301	60	34	17.8	23	NR
		Median	7.2	249	63	33	19.0	23	NR
		Maximum	7.5	725	82	50	26.0	40	NR
Hall 1987	May 1984[a]	Single Grab Sample	6.7	150	52	NR	NR	NR	NR
Hall 1987	April, May, June 1984	Minimum	6.2	NR	NR	NR	NR	NR	NR
		Mean	7.1	NR	NR	NR	NR	NR	NR
		Median	7.1	NR	NR	NR	NR	NR	NR
		Maximum	7.7	NR	NR	NR	NR	NR	NR
Hall 1987	April 1985[a]	Single Grab Sample	6.9	1600[b]	218[b]	40	NR	19	NR
James et al. 1988	October 1986 to September 1987	Minimum	7.0	152	48	20	14.0	<10	3.9
		Mean	7.2	252	61	45	18.0	39	6.0
		Median	7.3	243	60	44	17.5	40	5.8
		Maximum	7.7	760	83	66	26.0	150	8.5
James et al. 1992	October 1990 to September 1991	Minimum	6.5	144	39	25	11.0	<10	3.2[c]
		Mean	7.1	256	63	46	18.7	39	5.4[c]
		Median	7.1	246	60	45	18.5	40	4.9[c]
		Maximum	7.9	365	81	66	25.0	150	15.0[c]
Hall et al. 1991	May 1989[a]	Single Grab Sample	7.5	200	58	38	NR	36	NR

[a]Sample collected off Ferry Landing Road near Dunkirk, MD (62 km from river mouth).
[b]Salinity = 1.1 ppt.
[c]Total organic carbon (mg/L).

and defined as sensitive to acidic inputs (Knapp et al. 1988a).

The effects of acid and aluminum pulses of different magnitudes and durations on American shad eggs and larvae were conducted in either a continuous flow, solenoid-activated dilution and toxicant delivery system described in Klauda and Palmer (1986), or in a gravity-fed, continuous-flow system composed of four circular test tanks (0.81 m diameter x 0.23 m depth; 120 L volume) in which the test chambers containing test organisms were placed (Klauda et al. 1992). Flow rates through the two testing systems ranged from 100 to 200 ml/min. Photoperiod was maintained at 12 h light: 12 h darkness. Light intensities at the surface of the test tanks ranged from 206 to 515 lx.

Fertilized eggs were held during testing in gray cylindrical polycarbonate test chambers of two sizes (either 12 cm high x 8 cm diameter with an enclosed water volume of 0.6 L, or 14.8 cm high x 11.2 cm diameter with an enclosed water volume of 1.4 L). Each test chamber was fitted with 243 m mesh Nitex screen panels in the bottom and a threaded lid. Prefeeding and feeding larvae were held during testing in open-top, cylindrical, translucent polyethylene test baskets (27.0 cm high x 19.2 cm diameter x 7.8 L submerged volume). Each basket contained four side-wall openings (7.5 cm x 10.0 cm) covered with 243 m mesh Nitex screen. Feeding-stage larvae were fed brine shrimp nauplii twice daily during each experiment.

All head tanks and test tanks were aerated vigorously to ensure mixing of acid and aluminum additions as well as aeration and degassing of the reconstituted well water. Dissolved oxygen levels in the test tanks during the 11 experiments ranged from 8 to 11 mg/L. Reagent grade sulfuric and nitric acids (2:1 mixture) and aluminum (anhydrous $AlCl_3$) were added to the test water to produce the acid and aluminum treatments listed in Table 9.

TABLE 8.—Selected water quality data compiled to characterize the acid sensitivity of the Susquehanna River at Conowingo, MD (16 km upstream from river mouth), and in striped bass spawning areas of the upper Chesapeake Bay. NR = not reported.

Data source	Time period and location	Statistic	pH	Specific conductance (μS/cm)	Total hardness as $CaCO_3$ (mg/L)	Alkalinity (mg/L)	Dissolved Ca (mg/L)	Dissolved Al (μg/L)	Dissolved organic carbon (mg/L)
USGS 1980	October 1978 to September 1991	Minimum	7.1	110	33	12	9.3	<10	1.9
		Mean	7.8	212	77	35	20.8	42	3.2
		Median	7.9	215	67	31	18.5	40	2.7
		Maximum	8.4	335	120	59	33.0	150	6.1
James et al. 1984	October 1982 to September 1983	Minimum	7.2	138	52	22	14.0	<10	NR
		Mean	7.5	242	93	41	24.8	21	NR
		Median	7.5	207	92	39	25.0	15	NR
		Maximum	7.8	390	140	61	36.0	50	NR
Hall 1987	April, May, June 1984	Minimum	6.6	NR	NR	NR	NR	NR	NR
		Mean	7.7	NR	NR	NR	NR	NR	NR
		Median	7.7	NR	NR	NR	NR	NR	NR
		Maximum	8.4	NR	NR	NR	NR	NR	NR
James et al. 1988	October 1986 to September 1987	Minimum	6.8	130	61	25	17.0	<10	1.1[a]
		Mean	7.6	233	94	45	25.3	31	3.7[a]
		Median	7.6	237	88	43	24.0	30	3.5[a]
		Maximum	8.5	400	130	75	34.0	100	8.6[a]
Hall et al. 1991	April-May 1989	Minimum	7.2	95	40	15	NR	15	NR
		Mean	7.4	738	134	30	NR	42	NR
		Median	7.4	210	80	30	NR	30	NR
		Maximum	7.9	4800[c]	548[c]	55	NR	367	NR
James et al. 1992	October 1990 to September 1991	Minimum	6.4	136	50	28	14.0	<10	1.9[a]
		Mean	7.0	235	92	43	24.3	31	3.3[a]
		Median	6.9	213	84	44	23.0	30	2.9[a]
		Maximum	7.5	395	140	60	35.0	70	7.0[a]
Hall et al. 1992	April-May 1990[b]	Minimum	7.4	120	40	25	NR	16	NR
		Mean	7.6	272	80	35	NR	288	NR
		Median	7.6	175	80	34	NR	268	NR
		Maximum	7.8	1550[d]	200[d]	45	NR	780	NR

[a]Total organic carbon (mg/L).
[b]At three stations (Spesutie Island, Grove Point, Howell Point) off mouth of Sassafrass River, MD.
[c]Salinity = 3.25 ppt.
[d]Salinity = 1.0 ppt.

Test organisms (eggs or larvae) were transferred from the hatching jars or rearing aquaria to the test chambers approximately 2 to 4 h before the start of each experiment. Eggs and prefeeding larvae were transferred directly into the various acid and aluminum treatment conditions during the constant exposure pilot experiments conducted in 1985 and 1986 (Table 9). Pulse (or episodic) exposure experiments conducted in 1987, 1989, and 1990 were designed to simulate the change in acid and aluminum components of storm-induced acidic events measured in several coastal plain Maryland tributaries. About 2 to 4 h after test organisms were transferred to the test chambers and placed in reconstituted well water (no acid or aluminum), pH was decreased from control levels (7.1 to 7.6) to the desired pH over a 4 to 7 h pre-pulse period, maintained there for the desired pulse duration (4, 8, 16, 24, or 48 h), and then gradually returned to control conditions over an 8 to 12 h post-pulse period. See Klauda and Palmer (1987) for examples of typical pH profiles measured during such pulse exposure experiments. As pH was reduced in the test tanks, concentrations of inorganic aluminum were simultaneously increased to desired levels, maintained there for the same pulse durations as the acid, and then returned to control conditions within the 8 to 12 h post-pulse period. Control organisms for the pulse exposure experiments were handled exactly as test organisms, except they encountered only constant exposure to reconstituted well water (pH 7.1 to 7.6).

Mortality was the test response measured immediately after termination of each constant exposure experiment, or 12 to 14 h after the acid and aluminum pulses were over and water chemistry in the treatment tanks had returned to prepulse conditions in each pulse exposure experiment. All test organisms (dead and alive) were counted and recorded. Criteria for death of eggs and larvae were given in Klauda and Palmer (1987) and Klauda et al. (1987).

Lethal and Critical Conditions

One study objective was to use the observed mortality data derived from the laboratory experiments to define lethal and critical conditions for the exposure of American shad eggs and larvae to acid and aluminum pulses. For this paper, "lethal conditions" were defined as those levels of acidity only or acidity plus aluminum associated with 91 to 100% direct mortality of test organisms measured at the end of each laboratory experiment. Lethal conditions were therefore defined by those acid and aluminum treatments that killed most or all test organisms during the 11 experiments. "Critical conditions" were defined as levels of acidity only or acidity plus aluminum associated with at least 50% and as much as 90% direct mortality of test organisms measured at the end of each laboratory experiment. The concept of critical conditions is captured by several toxic effects criteria that have been applied to many contaminants. These criteria include the traditional acute effects benchmarks of time to 50% lethality at a given toxicant concentration (LT50); the toxicant concentration that is lethal to 50% of the test organisms in some specified time period such as 24, 48, or 96 h (LC50); and the lowest toxicant concentration that significantly increases mortality of the test organisms compared to observed mortality in the control groups.

The definition of critical conditions used in this paper focused on direct mortality during each experiment as the test response. Delayed mortality effects caused by exposure to acid and aluminum, and sublethal effects such as reduced growth rates, impaired feeding ability, or diminished predator avoidance capability that could indirectly affect test organism survival were not captured in this definition of critical conditions. Influence of avoidance behavior or the presence of refugia on fish survival were also not included in this definition of critical conditions.

Selection of a 50% direct mortality as the lower threshold for my definition of critical conditions

TABLE 9.— Overview of 11 laboratory experiments conducted by Klauda and colleagues to measure the sensitivity of American shad eggs and larvae to acid and aluminum in the laboratory. The endpoint for each experiment was direct mortality. NT = not tested, acid exposures only.

Year	Life stage (egg source)	Age at testing	Type of exposure	Test duration (h)	Range of pH exposures	Range of aluminum exposures (μg/L)	Reference
1985	Fertilized egg (James River, VA)	24-h post fertilization	Constant	96	5.0 - 7.8	0 - 400 (nominal)	Klauda and Palmer 1987
1986	Pre-feeding yolk-sac larva (Columbia River, WA)	1-d posthatch	Constant	55	5.4 - 7.7	11 - 460 (measured as total dissolved)	Klauda and Palmer 1987
1987	Prefeeding yolk-sac larva (Columbia River, WA)	2-d posthatch	Episodic (4, 8, 16 h pulses)	22	single pulses to 5.2, 6.2	single pulses to 45 - 79 (measured as total dissolved)	Klauda et al. 1988
1987	Feeding post yolk-sac larva (Columbia River, WA)	9-16 d posthatch	Episodic (4, 8, 16 h pulses)	22	single pulses to 5.2, 6.2	single pulses to 45 - 79 (measured as total dissolved)	Klauda et al. 1988
1989	Prefeeding yolk-sac larva (Columbia River, WA)	96-h post fertilization	Episodic (48 h pulse)	65	single pulses to 4.1 - 6.0	NT	Klauda et al. 1992
1989	Prefeeding yolk-sac larva (Columbia River, WA)	1-3 d posthatch	Episodic (24, 48h pulses)	40,65	single pulses to 4.1 - 6.0	single pulses to 26 - 71 (measured as inorganic monomeric)	Klauda et al. 1992
1989	Feeding post yolk-sac larva (Columbia River, WA)	6-7 d posthatch	Episodic (24 h pulse)	40	single pulses to 4.8 - 6.0	single pulses to 26- 71 (measured as inorganic monomeric)	Klauda et al. 1992
1990	Prefeeding yolk-sac larva (Delaware River, PA)	1-d posthatch	Episodic (24 h pulse)	40	single pulses to 4.0 - 6.0	single pulses to 22- 530 (measured as inorganic monomeric)	Unpublished

relates to the traditional LC50 measure of acute toxicity effects (and its variants such as LD50) that are widely reported in the aquatic toxicity literature. Use of an acute toxicity criterion for critical conditions, 50 to 90% direct mortality, avoids the uncertainty associated with quantification and translation of sublethal toxic effects to the probability of survival for exposed individuals, cohorts, or age groups. A 50% direct mortality criterion also represents a substantial increase in mortality above the 0 to 30% range that is typically observed in control groups of the delicate early life stages for anadromous Chesapeake Bay fish species during carefully designed and managed laboratory experiments (Klauda 1989). In summary, selection of a 50 to 90% direct mortality criterion to define critical acid and aluminum conditions for constant and pulse exposure experiments with American shad eggs and larvae in the laboratory is anchored to the premise that an increase in direct mortality of 20 to 90%, compared to control groups, should be viewed as an adverse toxic effect and a potentially significant increment of mortality on an American shad cohort.

Chemical Analyses

In each treatment tank, pH was measured with an Orion pH meter (model 231) and a Ross combination glass electrode (model 91-56) every 15 to 30 min during the pH decrease and nadir (pulse) periods, 2 or 3 times during the pH increase period, and once at the end of the experiment just before all test organisms were removed and counted. During most experiments, an unfiltered water sample was collected for aluminum analysis in a 60 ml syringe from each treatment tank at the start, before the acid was added, at the beginning of each acid pulse period, at the end of the pH nadir, and at the end of each experiment. Syringe samples were stored and transported in the dark at 4°C prior to analysis for total and organic monomeric aluminum within 24 h after collection using the pyrocatechol violet flow injection method (Henshaw et al. 1987; Knapp et al. 1988b). Concentrations of inorganic monomeric aluminum were obtained by subtraction (total monomeric minus organic monomeric). During some experiments (Table 9), only total dissolved aluminum was measured. These measurements were made from filtered water samples (0.45 m filter) by atomic absorption spectrophotometry (Perkin Elmer model 2380 equipped with a graphite furnace).

Total hardness (EDTA titration), specific conductance (YSI model 33 S-C-T meter), temperature (mercury thermometer), dissolved oxygen (Orion electrode), dissolved organic carbon (infrared spectrophotometry, EPA method 415.2), dissolved inorganic carbon (infrared spectrophotometry, EPA method 415.2), acid neutralizing capacity (modified Gran titration), major cations, major anions, and several trace metals were measured using methods described in APHA (1985), Hillman et al. (1986) and Knapp et al. (1988b).

TABLE 10.– Concentrations of analytes in the test water (demineralized and reconstituted well water) used for the episodic laboratory experiments with American shad eggs and larvae conducted between 1985 and 1990. Concentrations are in mg/L unless stated otherwise.

Analyte	Measured concentration (mean ± 1 SD)
pH (units)	7.4 ± 0.2
Specific conductance (μS/cm)	77.5 ± 3.4
Hardness (as $CaCO_3$)	25.7 ± 4.1
Acid neutralizing capacity (μeq/L)	548.8 ± 28.7
Dissolved organic carbon	0.9 ± 0.05
Dissolved inorganic carbon	5.4 ± 0.12
Calcium	7.4 ± 0.1
Magnesium	1.1 ± 0.2
Sodium	1.1 ± 0.2
Potassium	0.4 ± 0.05
Strontium	0.06
Chloride	0.7 ± 0.3
Sulfate	7.4 ± 0.8
Nitrate	0.8 ± 0.05
Iron	0.1 ± 0.05
Manganese	0.8 ± 0.4
Copper	<0.001
Cadmium	<0.001
Chromium	0.002
Zinc	<0.01
Arsenic	<0.001
Selenium	<0.001
Total monomeric aluminum (μg/L)	9.7 ± 0.9
Organic monomeric aluminum (μg/L)	4.7 ± 1.7
Inorganic monomeric aluminum (μg/L)	5.0 ± 0.8

Statistical Analyses

A General Linear Models procedure, the Student Newman Keuls test, and the Least Squares Mean test provided by SAS (SAS Institute 1985) were used to analyze the results of the laboratory experiments. The response variable, mortality, was a logit transformation of the proportion of test organisms that died during each experiment (Cox 1977; Ashton 1982). A Duncan's Multiple Range Test was used to test for significant differences in mortality among acid and aluminum treatments.

Results

Eggs. Results of the 96-h constant exposure pilot experiment conducted in 1985 (Table 11) showed that American shad eggs exposed to a range of acid and aluminum conditions beginning at 24-h post-fertilization tolerated pH 5.7 treatments (with no aluminum) and pH 6.5 treatments with 50, 200 and 400 g/L of aluminum (nominal concentrations). Eggs were more sensitive to five treatments that resulted in 50 to 90% direct mortality. These five treatments were therefore defined as critical conditions: pH 6.5 with no aluminum; pH 6.5 plus 100 g/L aluminum; pH 5.7 plus 50 g/L aluminum; pH 5.7 plus 200 g/L; and pH 5.0 with no aluminum. Five other treatments were even more stressful, resulting in 91 to 100% egg mortality and were therefore defined as lethal conditions: pH 5.7 plus 100 g/L aluminum; pH 5.7 plus 400 g/L aluminum; pH 5.0 plus 50 g/L aluminum; pH 5.0 plus 100 g/L aluminum; pH 5.0 plus 200 g/L aluminum; and pH 5.0 plus 400 g/L aluminum.

The 65-h pulse exposure laboratory experiment conducted during spring 1989 showed that 96-h post-fertilization eggs could survive a single acid-only pulse to pH 6.0 or 5.0 for 48 h with relatively low mortality (Table 12). This experiment did not reveal any critical conditions, but it did demonstrate that lethal conditions for fertilized shad eggs (94% mortality) occurred when they were exposed to a 48 h duration acid pulse at pH 4.1.

Prefeeding Larvae. The single constant exposure pilot experiment conducted during 1986 with prefeeding American shad larvae indicated that this life stage was very sensitive to all but one treatment (Table 13). Only prefeeding larvae exposed to the treatment of pH 6.6 with 11 g/L aluminum (total dissolved) and the control group exhibited good survival after 55 h of continuous exposure. All but four acid and aluminum treatments resulted in 100% direct mortality (lethal conditions) after 55 h of exposure. Six of 15 treatments resulted in greater than 50% direct mortality after 24 h of continuous exposure. The least severe treatment that resulted in at least 50% but less than 91% direct mortality (a critical condition treatment) was a 24 h exposure to pH 6.1 with 92 g/L of total dissolved aluminum. The least severe treatment that resulted in a lethal condition effect (91 to 100% mortality) was a 24 h exposure to pH 5.5 with 214 g/L of total dissolved aluminum.

Prefeeding larvae appeared to be very sensitive to dissolved aluminum during this constant exposure experiment. Mortality was low (14%) in the test group exposed to pH 6.6 only (with no aluminum) for 55 h. However, mortality increased to 32% after 24 h of exposure and 98% after 55 h when 57 g/L of total dissolved aluminum (about 30 g/L of total monomeric aluminum; Klauda and Palmer 1987) were added to the pH 6.6 treatment.

During 1987, 1989, and 1990, four pulse exposure experiments were conducted with prefeeding larvae. The larvae were able to tolerate a single acidic pulse from pH 7.6 to 6.2 for up to 16 h, either without aluminum or accompanied by a simultaneous pulse of total dissolved aluminum that ranged from 54 to 79 g/L (Table 14). Larval mortalities associated with these treatments ranged from 19 to 38%. By comparison, prefeeding larvae experienced 51% mortality after a 16 h exposure to a single acid pulse from pH 7.6 to 5.2 with no aluminum (a critical condition). A simultaneous aluminum pulse of 63 g/L (as total dissolved) for 16 h increased larval mortality to 83% (another critical condition). None of the treatments tested during this 1987 pulse exposure experiment resulted in lethal conditions for prefeeding larvae.

Three pulse exposure experiments with prefeeding larvae were conducted in 1989. However, because control group mortality was unexplainably high in two experiments, 67 and 71% (Table 15), the results are inconclusive and should be viewed with caution. The single experiment with prefeeding larvae that had acceptable control group mortality (mean of 19%) suggested that one critical condition was a single 24 h acid-only pulse of pH 4.8 (64% mortality). The 1989 experiments also suggested that prefeeding larvae were very sensitive to relatively low concentration pulses of inorganic monomeric aluminum (24 to 71 g/L) for 24 and 48 h durations; however, these apparently lethal conditions were obscured by the unexplained high control group mortality (Table 15).

High control group mortality (52%) was also a problem during a single pulse experiment conducted in 1990 with prefeeding larvae (Table 16). Compared to the control group that was exposed to pH 7.5 water with no added aluminum, larval mortality was relatively low (33-48%) during exposure to a 24 h acid pulse to pH 6.0 accompanied by an inorganic monomeric aluminum pulse to 22 or 25 g/L. However, prefeeding larvae were unable to tolerate 24 h exposures to single acid pulses to pH 5.0 or 4.0 that were accompanied by inorganic monomeric aluminum pulses that ranged from 58 to 136 g/L at pH 5.0 and from 102 to 530 g/L at pH 4.0, but neither critical nor lethal acidity conditions were conclusively revealed for prefeeding larvae because of the high control group mortality. The results suggest, however, that the critical pH for a single 24 h acidic pulse is between 5.0 and 6.0. Lethal conditions for prefeeding shad larvae during a 24-h acid only pulse appeared to be slightly above pH 5.0.

Feeding Larvae. American shad larvae that had absorbed their yolks and were feeding exogenously on brine shrimp nauplii for several days prior to testing appeared to be more sensitive to acid and aluminum pulses than the prefeeding larvae. These observations came from pulse exposure experiments conducted during 1987 (Table 17 compared to Table 14) and 1989 (Table 18 compared to Table 15). The 1987 experiment (Table 17) indicated that one lethal acidity condition for feeding larvae was a single acid pulse to pH 5.2 for 16 h plus a single aluminum pulse of 63 g/L (total dissolved), the most severe treatment tested. Several treatments produced critical acidity conditions. The least severe treatment that caused at least 50% but less than 91% direct mortality was a single acid-only pulse to pH 6.2 of 4 h duration (68% mortality).

Results of the 1989 experiments (Table 18) were obfuscated by unexplained high control group mortalities (82% and 85%). Larval mortality was also high (40% to 100%) in all 24 h pulse duration treatments. Because of high control group mortalities, critical and lethal acidity conditions for feeding-stage shad larvae were not clearly determined by the 1989 experiments.

Comparisons of American Shad and Fathead Minnow Larvae. Feeding-stage fathead minnow larvae were tested simultaneously with prefeeding American shad larvae during 24 h duration, single pulse exposure experiments in 1989 and 1990 and with feeding-stage shad larvae in 1989. The objective of these comparison tests was to provide a species sensitivity reference for shad larvae. Fathead minnows have been extensively tested to evaluate their responses to an array of contaminants, including acid and aluminum, and are reported to be a relatively sensitive fish species.

The results of the 24 h duration pulse exposure experiment with prefeeding shad larvae and feeding fathead minnow larvae (Table 15) that exhibited acceptable control group mortalities (18% for shad and, 19% for fathead minnows) suggested that fathead minnow larvae were much more sensitive than shad larvae to a single acid-only pulse to pH 5.9, but only slightly more sensitive to a single acid-only pulse to pH 4.8. However, when all treatments were considered, this experiment indicated similar critical and lethal acidity conditions for prefeeding shad larvae and feeding fathead minnow larvae.

The results of the other 1989 experiment (Table 15) and the 1990 experiments (Table 16) are inconclusive because of high control group mortality for prefeeding shad larvae (52% to 71%). These preliminary results at least suggest that prefeeding shad larvae were more sensitive than feeding-stage fathead minnow larvae to all except the most severe 24 h duration acid and aluminum treatments. One critical acidity condition for fathead minnow larvae revealed by the 1989 experiments was an acid-only 24h pulse to pH 4.8 that resulted in 85% mortality (Table 15). The 1990 experiment (Table 16) suggested that another critical condition for fathead minnow larvae was a single 24h pulse

TABLE 11.— Sensitivity of 24-h postfertilization American shad eggs (source: James River, VA) to acid and aluminum during a 96-h constant exposure laboratory test conducted in 1985 (details reported in Klauda and Palmer 1987). Treatment results are presented from highest to lowest observed mortality (two replicates combined).

Nominal pH	Nominal aluminum (μg/L)	Percent mortality
5.0	200	100
5.0	100	100
5.7	400	100
5.0	400	96
5.0	50	96
5.7	100	92
5.7	200	86
5.7	50	84
5.0	0	65
6.5	100	63
6.5	0	60
6.5	200	28
6.5	50	13
6.5	400	4
5.7	0	0

to pH 5.0 with a single aluminum pulse to 58 g/L (as inorganic monomeric) that resulted in 54% mortality. The least severe treatments associated with 91 to 100% direct mortality of fathead minnow larvae (defined as lethal conditions) were a 24 h acid pulse to pH 5.0 with a single aluminum pulse to 71 g/L (97% mortality) and a 24 h acid pulse to pH 5.0 with an inorganic monomeric aluminum pulse to 75 g/L (93% mortality; Tables 15 and 16).

The sensitivity of feeding-stage shad larvae to acid and aluminum was also compared with feeding-stage fathead minnow larvae during the 1989 pulse exposure experiments (Table 18). The unexplainably high control group mortality for shad larvae obscured any definitive conclusions about apparent differences. These preliminary results suggest that feeding-stage shad larvae were more sensitive than feeding-stage fathead minnow larvae to moderately severe acid and aluminum treatments, and about equally sensitive to the most severe treatments.

TABLE 12.—Sensitivity of 96-h postfertilization American shad eggs (source: Columbia River, WA) to acid only during a 65-h episodic exposure laboratory test conducted in 1989 (details reported in Klauda et al. 1992). Treatment results are presented from highest to lowest mortality (two replicates combined).

pH pulse magnitude	Pulse duration (h)	Percent mortality
7.5 to 4.1	48	94
7.5 to 5.0	48	30
7.5 to 6.0	48	2
None (7.5)	65	0

Discussion

American shad spawn from early March through April in the tidal freshwater portions of several Maryland rivers that flow into the Chesapeake Bay (Klauda et al. 1991). The semi-demersal to pelagic, non-adhesive fertilized eggs hatch in 2 d at a water

TABLE 13.— Sensitivity of 1-d posthatch, prefeeding American shad yolk-sac larvae (source: Columbia River, WA) to acid and aluminum during a 55-h constant exposure laboratory test conducted in 1986 (details reported in Klauda and Palmer 1987). Treatment results are presented from highest to lowest mortality after 55 hours (two replicates combined). NM = not measured.

	Aluminum (µg/L)		Percent mortality	
Mean measured pH	Nominal	Measured[a]	After 24 h	After 55 h
5.7	400	NM	100	100
6.2	400	NM	100	100
6.7	400	460	100	100
5.5	200	214	92	100
6.1	200	NM	82	100
6.1	100	92	52	100
5.5	100	NM	46	100
5.4	50	79	33	100
6.0	0	11	29	100
6.9	200	182	31	100
5.4	0	11	23	100
6.1	50	61	29	98
6.6	50	57	32	98
6.8	100	81	24	92
6.6	0	11	6	14
7.7	0	11	0	6

[a]Total dissolved.

temperature of 27°C and 17 d at a water temperature of 12°C. The yolk-sac larvae are 6 to 10 mm in total length (TL) at hatching, and can begin to feed exogenously at 4 to 7 d post-hatch. The feeding-stage larvae are photopositive, most abundant near the surface in fresh and brackish waters up to about 7 ppt salinity, move gradually downstream as they develop, and complete metamorphosis to the juvenile stage in 3 to 4 weeks at about 25 to 28 mm TL.

The fertilized eggs, prefeeding (yolk-sac) larvae, and to a lesser degree, the young feeding (post yolk-sac) larvae are the life stages of American shad that have the highest probability for exposure to temporary episodes of pH depressions and elevated aluminum levels in or near the freshwater spawning sites. Exposure of late-stage feeding larvae and early juveniles to the intermittent conditions is reduced, because these older stages move downstream, either passively or actively, from freshwater to slightly brackish areas. These brackish areas should have a higher buffering capacity and be less likely to experience pH depressions (Klauda 1989). However, because juvenile American shad spend their first summer in tidal freshwater, the late larvae and juveniles are still at some risk to pH depressions prior to their fall emigration to the sea.

The laboratory experiments described in this paper increase the amount of published information on the sensitivity of American shad early life stages to acid and aluminum exposures, especially pulse exposures. Although my results are preliminary (being based on relatively few experiments) and have not been field-validated (Eaton et al. 1992), the data permit at least some tentative answers to the first two questions that this paper set out to address:

1) *Are American shad eggs and larvae sensitive to acid and aluminum exposures that reflect periodic environmental conditions observed in some Maryland spawning rivers?* The answer to this question is yes, although American shad eggs were less sensitive to acid and aluminum pulses than were the two larval stages, a pattern also observed with the eggs and prefeeding larvae of blueback herring (Klauda and Palmer 1987; Klauda et al. 1987). A summary of the laboratory treatment results for American shad eggs and larvae separated into lethal and critical mortality responses is presented in Table 19.

2) *What are the lethal and critical acid and aluminum conditions for American shad eggs and larvae?* The acid-only treatment that caused at least 91% direct mortality of fertilized eggs was a 48 h

TABLE 14.— Sensitivity of 2-d posthatch, prefeeding American shad yolk-sac larvae (source: Columbia River, WA) to acid and aluminum during a 22-h episodic exposure laboratory test conducted in 1987 (details reported in Klauda et al. 1988). Treatments results are presented from highest to lowest mortality (two replicates combined).

pH pulse magnitude	Peak total dissolved aluminum during pulse (µg/L)	Pulse duration (h)	Percent mortality
7.6 to 5.2	63	16	83
7.6 to 5.2	None	16	51
7.6 to 6.2	None	4	37
7.6 to 6.2	None	16	38
7.6 to 5.2	None	8	36
7.6 to 6.2	None	8	32
7.6 to 5.2	46	8	28
7.6 to 6.2	79	16	27
7.6 to 5.2	None	4	23
7.6 to 6.2	74	4	20
7.6 to 6.2	54	8	19
7.6 to 5.2	45	4	16

exposure to pH 4.1. However, fertilized eggs succumbed to less severe acid pulses lasting 96 h when the acidity was accompanied by moderate levels of aluminum. Critical conditions (50 to 90% direct mortality) for eggs ranged widely from pH 5.0 (with 100 g/L of aluminum) to pH 6.5 (with no aluminum).

Bradford et al. (1968) reported that fertilized American shad eggs showed some development at pH 4.0, 4.5, and 5.0 (acid-only treatments, no aluminum), but only 0 to 8% hatched at pH 5.0 and only 32% hatched at pH 5.2. None of the eggs hatched that were incubated at pH 3.0, 3.5, 4.0, and 4.5. These laboratory experiments were conducted at 18°C and lasted about 3 to 4 d. Although 86 to 99% of the exposed eggs hatched in the pH 5.5 treatment, 17 to 81% of the larvae either died soon after hatching or were severely deformed. The best hatching success and initial larval survival observed by Bradford et al. resulted from eggs incubated at pH 6.0 to 7.5. They calculated an LD50 (lethal acid dose associated with 50% mortality) for eggs of about pH 5.5.

My laboratory results with American shad eggs are consistent with the lethal pH conditions observed during the constant condition exposures conducted by Bradford et al. (1968). However, my results for constant and episodic exposure to acid and aluminum also suggest that critical pH conditions (no aluminum) for shad eggs ranged widely from pH 5.0 to pH 6.5. The critical condition threshold was near pH 6.5 if single acid pulses were accompanied by single aluminum pulses of about 100 g/L.

Acid and aluminum treatments associated with lethal and critical conditions in prefeeding American shad larvae also ranged widely. The least severe lethal mortality treatments were 55 h exposures to treatments in the mid to high pH 6 range, accompanied by aluminum pulses that ranged from 57 to 460 g/L. Shorter duration acid-only pulses also appeared to be lethal between pH 4.0 and 5.0. The critical conditions for direct mortality of prefeeding shad larvae were pH depressions to 6.0 or 6.1 that lasted at least 24 h and were accompanied by 26 to 200 g/L aluminum pulses.

Lethal acidic conditions for feeding American shad larvae were not conclusively defined by my laboratory experiments, but larvae succumbed to a single 16 h acid pulse to pH 5.2 accompanied by a 63 g/L aluminum pulse. The least severe critical condition treatments were relatively short duration exposures (4 or 8 h) to acid-only pulses to pH 6.2 and acid with aluminum pulses to pH 6.2 (79 g/L of aluminum) that lasted for 8 h (Table 19). With regard to critical conditions, feeding stage shad lar-

TABLE 15.— Sensitivity of 1 to 3-d posthatch, prefeeding American shad yolk-sac larvae (source: Columbia River, WA) and fathead minnow larvae to acid and aluminum during 40 and 65-h episodic exposure laboratory tests conducted in 1989 (details presented in Klauda et al. 1992). Treatment results are presented from highest to lowest mortality for American shad (two replicates combined).

pH pulse magnitude	Peak inorganic monomeric aluminum during pulse (µg/L)	Pulse duration (h)	Percent mortality	
			American shad	Fathead minnow
7.5 to 4.1	None	48	100[a]	NT
7.5 to 4.9	53	24	100[a]	99
7.5 to 5.0	71	24	100[a]	97
7.5 to 6.0	26	24	87[a]	0
7.5 to 5.0	None	48	76[a]	0
None (7.5)	None	40	71[b]	1
None (7.5)	None	65	67[b]	NT
7.5 to 4.8	None	24	64	85
None (7.5)	None	40	18	19
7.5 to 6.0	None	48	17[a]	NT
7.5 to 5.9	None	24	9	47

[a]Inconclusive because of high control group mortality.
[b]Unexplained high control group mortality.

TABLE 16.— Sensitivity of 1-d posthatch, prefeeding American shad yolk-sac larvae (source: Delaware River, PA) and fathead minnow larvae to acid and aluminum during a 40-h episodic exposure laboratory test conducted in 1990 (unpublished data). Treatment results are presented from highest to lowest mortality for American shad (two replicates combined).

pH pulse magnitude	Peak inorganic monomeric aluminum during pulse (μg/L)	Pulse duration (h)	Percent mortality: American shad	Percent mortality: Fathead minnow
7.5 to 4.0	530	24	100[a]	100
7.5 to 4.0	276	24	100[a]	100
7.5 to 4.0	165	24	100[a]	100
7.5 to 4.0	102	24	100[a]	100
7.5 to 4.0	None	24	100[a]	100
7.5 to 5.0	136	24	100[a]	100
7.5 to 5.0	75	24	100[a]	93
7.5 to 5.0	58	24	99[a]	54
7.5 to 5.0	None	24	74[a]	28
None (7.5)	None	24	52[b]	0
7.5 to 6.0	None	24	48[a]	3
7.5 to 6.0	25	24	41[a]	1
7.5 to 6.0	22	24	33[a]	3

[a]Inconclusive because of high control group mortality.
[b]Unexplained high control group mortality.

TABLE 17.— Sensitivity of 9 to 16-d posthatch, feeding American shad post yolk-sac larvae (source: Columbia River,WA) to acid and aluminum during a 22-h episodic exposure laboratory test conducted in 1987 (details reprinted in Klauda et al. 1988). Treatment results are presented from highest to lowest mortality (two replicates combined).

pH pulse magnitude	Peak total dissolved aluminum during pulse (μg/L)	Pulse duration (h)	Percent mortality
7.6 to 5.2	63	16	100
7.6 to 5.2	None	16	83
7.6 to 6.2	79	16	70
7.6 to 6.2	None	4	68
7.6 to 6.2	None	8	67
7.6 to 6.2	54	8	58
7.6 to 5.2	None	4	56
7.6 to 5.2	46	8	54
7.6 to 5.2	45	4	48
7.6 to 6.2	None	16	35
7.6 to 6.2	74	4	34
7.6 to 5.2	None	8	23

TABLE 18.— Sensitivity of 6 to 7 d posthatch feeding American shad post yolk-sac larvae (source: Columbia River, WA) and fathead minnow larvae to acid and aluminum during 40-h episodic exposure laboratory tests conducted in 1989 (details presented in Klauda et al. 1992). Treatment results are presented from highest to lowest mortality for American shad (two replicates combined).

pH pulse magnitude	Peak inorganic monomeric aluminum during pulse (μg/L)	Pulse duration (h)	Percent mortality	
			American shad	Fathead minnow
7.5 to 4.8	None	24	100[a]	85
7.5 to 4.9	53	24	100[a]	99
7.5 to 5.0	71	24	100[a]	97
None (7.5)	None	40	85[b]	19
None (7.5)	None	40	82[b]	1
7.5 to 5.9	None	24	71[a]	47
7.5 to 6.0	26	24	40[a]	0

[a]Inconclusive because of high control group mortality.
[b]Unexplained high control group mortality.

vae (6 to 16d old) appeared to be more sensitive to acid and aluminum pulses than prefeeding larvae (1 to 3d old).

Klauda (1989) reviewed the available information on several migratory Chesapeake Bay fishes and concluded that American shad early life stages were more sensitive to acid and aluminum exposures than yellow perch *Perca flavescens*, alewife, and blueback herring, but somewhat less sensitive than striped bass and white perch. The results reported in this paper also suggest that American shad larvae are at least as sensitive to acid and aluminum exposures as the larvae of fathead minnow, and perhaps slightly more sensitive. Several studies have previously found that fathead minnows are relatively sensitive to acid and aluminum exposures (Mount 1973; Zischke et al. 1983; Palmer et al. 1988; McCormick et al. 1989). Klauda et al. (1992) reported that critical acidity conditions for feeding-stage fathead minnow larvae appeared to lie between pH 5 and 6 during single 24 h acid-only pulses. Concomitant pulses of inorganic monomeric aluminum (52.5 and 71.0 g/L) at pH 5 increased larval mortality compared to the same acid treatment without aluminum.

Can the results of these laboratory experiments with American shad eggs and larvae provide any answers to the remaining two questions that this paper set out to address?

3) *Could acid deposition and habitat acidification have contributed to American shad stock declines in Maryland* and

4) *Is habitat acidification slowing the recovery of some American shad stocks in Maryland?*

The answer to question 3 depends on the relative importance of biotic and abiotic factors on American shad recruitment. Although Maryland's Department of Natural Resources is collecting and analyzing information needed for the effective management of anadromous *Alosa* stocks, including American shad (Krantz et al. 1992), no studies are currently examining possible interactions among water quality factors, climatic or environmental variability, and American shad reproduction (Speir 1987).

There is no direct evidence that links habitat acidification to the declining stock size, but this is only one factor. Studies of American shad in the Connecticut River showed that stock size had almost no influence on the number of recruits that returned to spawn (Crecco 1978; Crecco and Savoy 1987). The determining factors that appeared to control year class success in this population were climatic or weather-related and focused on the prejuvenile stages. These findings for the Connecticut River, where American shad landings have remained relatively stable over the past 20 years (Richkus and DiNardo 1984), may not be completely relevant to the shad stocks that spawn in Maryland's portion of Chesapeake Bay. Maryland's American shad stocks have declined to very low levels, beginning in the mid to late 1950's, and have not yet recovered. Fisheries scientists acknowledge that when spawner population levels for those fish species that are typically regulated by density-independent (abiotic) factors (e.g., American shad) are relatively low and near the critical abundance threshold, fecundity and spawning stock biomass should play a more dominant role in determining the number of young produced than when the stock is relatively abundant (Klauda et al. 1991).

The array of biotic and abiotic factors that could act individually and in combination to influence year class success in American shad populations is complex (Figure 10). It is therefore difficult to distinguish the relative importance of any single factor. The dramatic declines in American shad stocks along the U.S. East Coast between the late 1800's and 1940's are generally attributed to overharvesting, construction of dams which prevented access of the adults to many spawning grounds, pollution, and siltation of spawning rivers (Walburg and Nichols 1967). Some combination of these factors were also responsible for the general decline in Chesapeake Bay stocks of American shad during this same time period.

But what factors can be implicated in the more recent decline in Maryland's shad stocks that began in the mid-1950's and accelerated during the early 1970's? Could acid deposition be an important component of pollution that contributed to the decline? .Speir (1987) stated that "stream acidification does offer a testable hypothesis for a single, widespread factor in the concurrent decline in reproduction of several species of anadromous fish", including American shad, in Maryland. But he also emphasized that the final scientific proof for the acid deposition hypothesis awaits establishment. Speir (1987) went on to conclude that "there are a variety of insults to the Chesapeake that have been documented which in combination or singly have the potential to have contributed to the decline in reproduction of anadromous fish." Klauda and Bender (1987) extended this view when they stated that "To date ...no direct link between acidic deposition, habitat acidification, and fish mortality has been established for any Maryland watershed." Although no direct identification has been made of a "smoking gun," acid deposition is one of several potential factors that may be contributing, in varying degrees, to the slow recovery of Maryland's shad stocks in some rivers and to the continuous decline in others (Figure 11). Knowledge about the effects of acidification on fish populations and communities is substantial in some freshwater systems, where a few clear linkages have been forged (Huckabee et al. 1989). But far less work has been done with migratory fish species like the American shad in estuarine areas (Hendrey 1987).

To forge a convincing link between the occurrence of intermittent episodes of pH depressions and aluminum elevations and reduced reproductive success of American shad is a formidable task that must be pursued systematically, particularly in the face of myriad natural and anthropogenic environmental factors that can alter early life stage survival. Based upon recognized methods of statistical inference (Mostellar and Tukey 1977; Cochrane 1983), the following criteria should be fulfilled to establish a high degree of confidence in any cause and effect relationship:

a) *consistency* - a strong pattern of spatial or temporal consistency should be observed between a specific effect or response (e.g., change in shad egg or larval survival, condition, or performance) and presence of the suspected causal factor (e.g., pH depressions in spawning and nursery areas);

b) *responsiveness* - a reproducible and quantitative relationship should be observed between the amount or extent of the suspected causal factor (e.g. frequency, magnitude, duration of toxic pH depressions) and the amount or extent of a given effect or response (e.g. increase in shad egg or larval mortality); and

c) *mechanistic* - a known biological, chemical, or physical mechanism, or a series of stepwise processes (e.g. biochemical, physiological, ecological, genetic) should be determined through research to link a given effect or response (e.g. increase in shad egg or larval mortality) to the suspected causal factor (e.g., pH depressions in spawning or nursery areas).

The test results presented in this paper represent the first step in the pursuit of a systematic scheme to fulfill these criteria. More research is needed. At the very least, our laboratory test results should be field-validated using *in situ* experiments, an approached advocated by Eaton et al. (1992).

Even if acidic deposition was not the most important factor responsible for the general decline in Maryland's American shad populations, it may have been relatively important in some of the state's rivers and could be acting in combination with other factors to slow stock recoveries in these acid-sensitive systems. It is hoped that the 1990 amendments to the federal Clean Air Act will significantly reduce the habitat acidification process at its source: nitrogen and sulfur emissions. The laboratory results presented in this paper argue for vigorous and timely implementation of the new Clean Air Act. With regard to pollution effects on fish populations in general, Sindermann (1980) argued that "to insist on demonstrations of easily discernable effects on overall species abundance is to establish too harsh a criterion of pollution damage. A much more acceptable concept is that effects of pollution, clearly demonstrated on even a single individual or a local population, must be considered a cause for management action to protect the total population - just as is the case with humans."

Natural mortality rates during the egg and larval stages of American shad are very high. Leggett (1977) reported that, on average, only 0.00083% of the eggs spawned produce sexually mature adults that return to spawn. Most of this high mortality occurs between egg deposition and the juvenile stage. Survival from the prefeeding or yolk-sac larva stage through the juvenile stage is about 1 to 2%. Year class strength for cohorts of American shad is apparently established during the first 20 d after hatching and before the larvae reach the juvenile stage (Crecco et al. 1983). Large annual fluctuations in year-class success for many fish species, including American shad, can be generated by surprisingly small differences in survival or growth rates during the egg and larval stages (Sissenwine 1984; Houde 1987). Therefore, even if acidic deposition was responsible for only a relatively minor amount of early life stage mortality in American shad stocks during some years in some Maryland rivers, it could be contributing to relatively large annual variations in year-class success and slowing stock recoveries in acid-sensitive rivers.

Acid deposition and associated temporary pH depressions accompanied by elevated levels of toxic aluminum may be relatively important factors in early life stage survival for American shad spawning in the Choptank and Nanticoke rivers (Figure 12). These two Eastern Shore Maryland rivers possess limited buffering capacity to acidic inputs. The freshwater areas where American shad spawn experience temporary, storm-related pH depressions to less than 6.0 and elevated monomeric aluminum concentrations greater than 50 to 100 g/L that can persist for several hours to several days during the spring spawning and early nursery periods. The laboratory study results presented in this paper suggest that these acid and aluminum conditions can substantially increase the mortality of American shad eggs and larvae, especially the prefeeding and early feeding stages.

The abundance of American shad stocks in the Choptank and Nanticoke rivers is currently very low; hence, the stocks are vulnerable to an array of environmental stressors, including acid deposition. Not since the late 1800's have either the Nanticoke River or the Choptank River contributed more than 10% of the total annual Maryland commercial landings of American shad. Acid deposition may be a factor contributing to slow stock recovery in these two Eastern Shore rivers.

Since the mid-1970's, commercial landings of American shad in the Choptank River have dwin-

TABLE 19.— Summary of laboratory treatments associated with lethal and critical mortality responses to acid and aluminum (Al)[a] pulses experienced by American shad eggs and larvae during the array of experiments described in this paper.

Life stage (age)	Lethal treatments (91 - 100% direct mortality)	Critical treatments (50 - 90% direct mortality)
Fertilized egg (24-96 h)	pH 5.7 + 100 or 400 μg/L Al for 96 h pH 5.0 + 50-400 μg/L Al for 96 h pH 4.1 for 48 h	pH 6.5 for 96 h pH 6.5 + 100 μg/L Al for 96 h pH 5.7 + 50 or 200 μg/L Al for 96 h pH 5.0 for 96 h
Prefeeding larva (1-3 d)	pH 6.6-6.9 + 57-460 μg/L Al for 55 h pH 6.2 + 400 μg/L Al for 24 h pH 6.1 + 61-92 μg/L Al for 55 h pH 6.0 for 55 h pH 5.5 + 214 μg/L Al for 55 h pH 4.9-5.0 + 53-136 μg/L Al for 24 h[b] pH 4.0 for 24 h[b] pH 4.0 + 102-530 μg/L Al for 24 h[b]	pH 6.1 + 92-200 μg/L Al for 24 h pH 6.0 + 26 μg/L Al for 24 h pH 5.2 for 16 h pH 5.2 + 63 μg/L Al for 16 h pH 5.0 for 48 h[b] pH 5.0 for 24 h[b] pH 4.8 for 24 h[b]
Feeding larva (6-16 d)	pH 5.2 + 63 μg/L Al for 16 h pH 4.9-5.0 + 53-71 μg/L Al for 24 h[b] ph 4.8 for 24 h[b]	pH 6.2 for 4 or 8 h pH 6.2 + 54 or 79 μg/L Al for 8 h pH 5.2 for 4 or 16 h pH 5.2 + 46 μg/L for 8 h

[a]Refer to Results section for the chemical forms of aluminum reported here.
[b]Inconclusive because of high control group mortality.

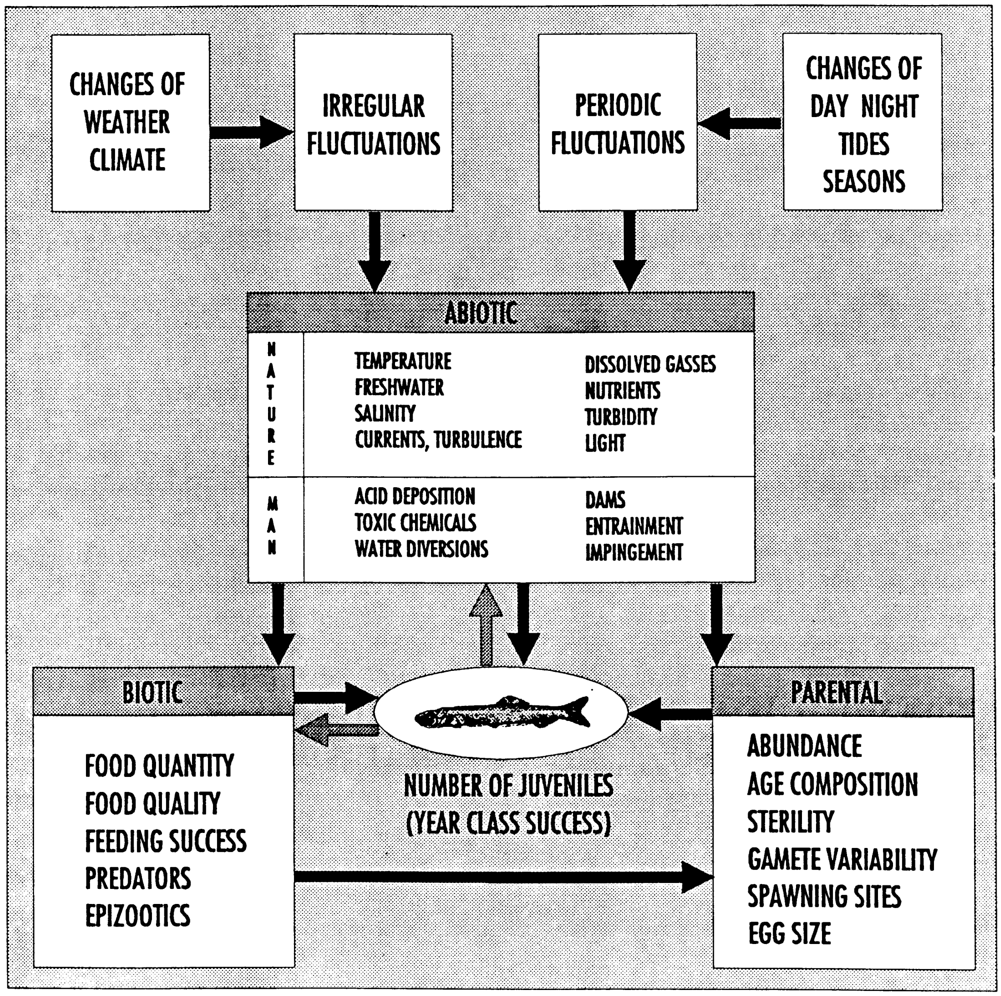

FIGURE 10.—Conceptual diagram that illustrates the array of biotic and abiotic factors that could influence year-class success of American shad.

dled to nearly zero. Klauda et al. (1991) conducted a qualitative assessment of the current status of the American shad spawning population in each major Chesapeake Bay tributary, compared to the late 1960's and early 1970's. They concluded that the Choptank River contains a remnant population that is at a very low level of abundance. No signs of American shad stock recovery is evident in the Choptank.

Klauda et al. (1991) also described the current status of American shad in the Nanticoke River. He concluded that it was at a low level of abundance but appeared to be stable. From a more quantitative perspective, Krantz et al. (1992) concluded that the American shad population in the Nanticoke River in 1991 was low. But a stable incidence of repeat spawners (about 10 to 20% between 1989 and 1991) and an increase in the numbers of virgin females (from 95 in 1988 to 301 in 1991), coupled with a relatively stable age composition, are encouraging signs that some stock recovery may be starting in this Eastern Shore river.

Acid deposition is probably not an important factor in the early life stage survival of American shad in the Potomac, Patuxent, or Susquehanna rivers or in the upper Chesapeake Bay (Figure 12). The buffering capacity is much higher in these Western Shore rivers that drain portions of the Piedmont physiographic province than in most rivers on Maryland's Eastern Shore. Temporary episodes of pH depressions below 6.5 have been rare to nonexistent in Western Shore shad spawning areas. The slightly elevated dissolved aluminum levels that have been periodically recorded in these systems at circumneutral pH's are not likely to be toxic to American shad early life stages (Baker 1982; Baker and Schofield 1982).

The currently depressed status of American shad in the Potomac, Patuxent, and Susquehanna rivers and the upper Chesapeake Bay, all relatively well-buffered spawning areas compared to Eastern Shore Maryland rivers, indicate that factors other than acid deposition are also important in the dynamics of Maryland shad stocks. Nevertheless, it

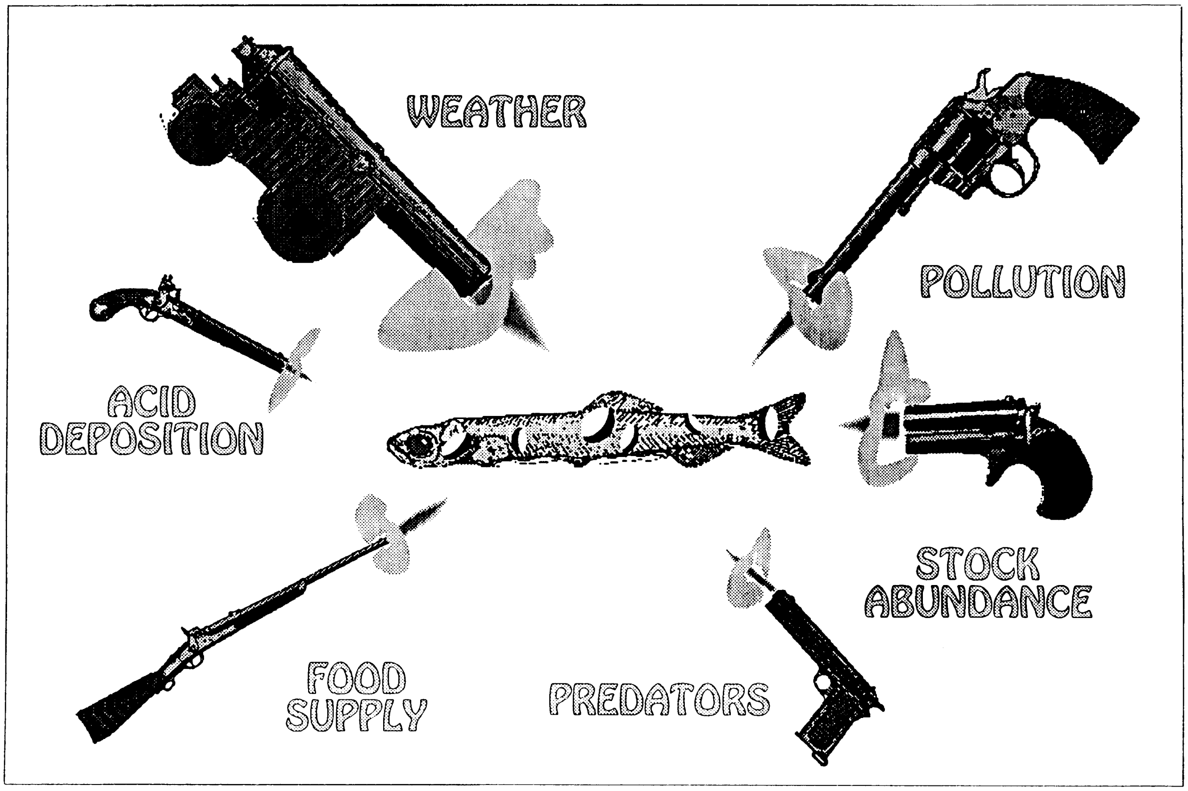

FIGURE 11.—Acid deposition is one of many potential "smoking guns" that may be slowing the recovery of American shad stocks in some Maryland rivers.

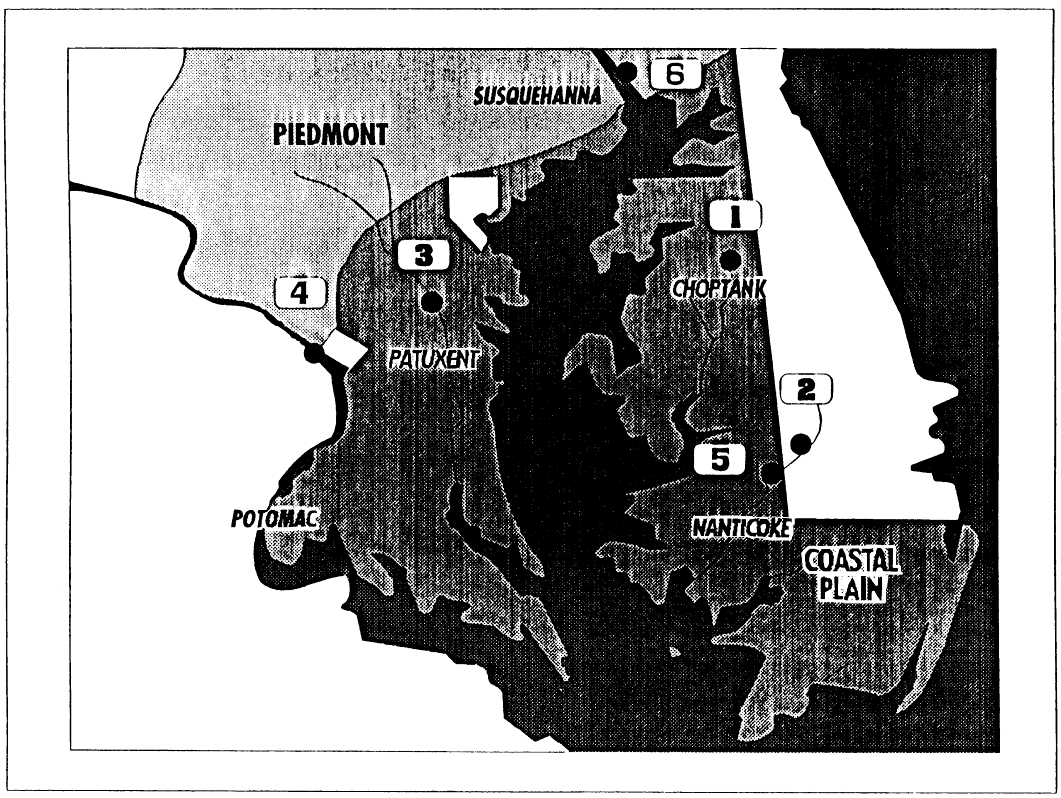

FIGURE 12.—Major tributaries to the Maryland portion of the Chesapeake Bay that are used for spawning by American shad. Numbers refer to water quality sampling stations discussed in the text; 1 = Choptank River near Greensboro, MD; 2 = Nanticoke River near Woodland Ferry, DE; 3 = Patuxent River near Bowie, MD; 4 = Potomac River at Chain Bridge; 5 = Nanticoke River near Sharptown, MD; 6 = Susquehanna River near Conowingo, MD.

can be hypothesized that whenever the abundance of an acid-sensitive fish species like American shad is as low as most Maryland stocks are today and annual climatic conditions are less than favorable for good reproduction, even infrequent and temporary episodes of critical or lethal pH and aluminum conditions in the spawning and nursery areas could contribute to significant reductions in egg or larval survival and thereby slow stock recovery. The results of the laboratory studies described in this paper suggest that those American shad stocks that spawn in poorly buffered Eastern Shore Maryland rivers, like the Nanticoke and Choptank, are vulnerable to storm-induced, toxic pulses of low pH and elevated aluminum, and may therefore recover at a much slower rate than Western Shore stocks, even if all other anthropogenic stressors are removed.

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Characteristics of the Early Life Stages of Cultured Alewife and Blueback Herring Emphasizing Identification of Larvae[1]

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Abstract.—Larval alewife *Alosa pseudoharengus* and blueback herring *A. aestivalis* are described from specimens hatched from eggs of known taxonomic identity and reared in outdoor tanks. No differences were observed in egg morphology or in the meristics and morphologies of larvae. Pigmentation of yolk-sac larvae and preflexion larvae did not differ between the species, although melanophores at the base of the caudal finfold dorsal to the tail were more common in blueback herring. Melanophores along the dorsal midline posterior to the dorsal fin developed earlier and were more numerous in alewife larvae than in blueback herring larvae following notochord flexion. Diagnostic pigment distributions were observed between postflexion larvae of the two species. In alewife, paired melanophores that increased in number with age were found along the lateral surface of the notochord at the level of the nape, and contracted xanthophores were scattered on the dorsal surface of the head. In blueback herring, one or two melanophores occurred on the dorsal surface of the notochord at the level of the nape, xanthophores covered the dorsal surface of the head over the brain, and xanthochrome occurred at the base of the caudal fin. Other differences in xanthic pigmentation were also identified.

Accurate identification of eggs and larvae is an essential element of early life history studies of fishes. Powles and Markle (1983) state: "Minor errors in identification of larval fishes can lead to major misinterpretations of ecological and taxonomic phenomena." For some groups (e.g. Clupeidae), larvae possess few morphometric characters which can be used to identify species. Numbers of myomeres or vertebrae have been suggested to be the primary taxonomic character for identifying larvae of closely related species, including clupeid larvae (Berry and Richards 1973; McGowan and Berry 1983). Total myomere counts for preflexion clupeid larvae can be difficult to obtain, however, due to indistinct separation of myomeres anterior to the cleithrum or posterior to the vent (Russell 1976).

Morphometric and meristic characters of some clupeid larvae appear to vary regionally which may limit their usefulness for determining species identity, especially when characters for larvae from one region are used to identify larvae from other regions (Bosley and Conner 1984). For example, the total number of myomeres and vertebrae of larval blueback herring *Alosa aestivalis* and larval gizzard shad *Dorosoma cepedianum* in the Santee-Cooper River, South Carolina, do not differ but are significantly greater than those of larval threadfin shad *D. petenense* (Bulak 1985). Santucci and Heidinger (1986) report greater total myomeres in gizzard shad larvae as compared to threadfin shad larvae, and they show regional variation in total myomeres for both species. Taber (1969 cited by Lam and Roff 1977), however, finds no difference in total myomeres and vertebrae for threadfin shad or gizzard shad in Lake Texoma, Oklahoma. In other cases, such as among marine clupeids, species identification of larvae of sympatric congeners may not be possible based solely on meristics and morphometrics and may be based upon supplemental data, such as date and location of capture (Houde and Fore 1973; Richards et al. 1974; Funes-Rodríguez and Esquivel-Herrera 1985). Species identification is simplified with complete formation of adult characters, such as dorsal, caudal, and anal finrays and gillrakers (Berry and Richards 1973; McGowan and Berry 1983).

Anadromous populations of alewife *A. pseudoharengus* and blueback herring are distributed along the eastern seaboard of North America. Blueback herring occur from Florida to New Brunswick and Nova Scotia, and alewife occur from South Carolina to Newfoundland and Labrador (Loesch 1987). These species support significant commercial and recreational (primarily dip-net) fisheries and are prey for numerous aquatic and terrestrial predators (Loesch 1987). The initiation of spawning by these species is temperature-dependent beginning earlier (December-February) in southern populations and

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occurring later (May-June) in northern populations; alewife spawning precedes blueback herring spawning by three to four weeks but there is considerable overlap in their spawning seasons (Loesch 1987). Tidal and nontidal reaches of coastal rivers along eastern North America are utilized for spawning and nursery habitat by alewife and blueback herring, and eggs and larvae of these species likely intermix during their freshwater residency (Dovel 1971; Lippson and Moran 1974; Marcy 1976; Wang and Kernehan 1979; Boreman 1981). Knowledge of the early life histories of alewife and blueback herring is limited by the inability to reliably identify the eggs and larvae of these species when collected in ichthyoplankton samples. A method for species identification would facilitate the analysis of the ecology and population dynamics of alewife and blueback herring larvae.

The usefulness of meristic and morphologic characters for identifying alewife and blueback herring larvae is unresolved. Chambers et al. (1976) suggested that alewife and blueback herring larvae may be delimited by the postdorsal-to-preanal myomere number and by the snout-to-vent length as a percentage of standard length (SL). In contrast, Cianci (1969) finds no significant differences in meristic or morphometric characters of larvae of these species. In addition, other studies which compared alewife or blueback herring larvae to gizzard shad and threadfin shad larvae provide indirect evidence that alewife and blueback herring larvae lack significant meristic and morphometric variation (see Discussion). Juvenile and adult characters useful for identifying these species are present at about 20 mm SL (Dovel et al. 1965; Wang 1970).

Pigmentation patterns are useful for the identification of larval fishes and to establish taxonomic relationships between species groups (Berry and Richards 1973; Ahlstrom and Moser 1976; McGowan and Berry 1983). Descriptions of pigment patterns in alewife and blueback herring larvae are, at present, limited to preflexion larvae and to late-stage postflexion larvae and early juveniles at transformation. Pigment patterns of alewife and blueback herring larvae between flexion (about 9-11 mm SL) and transformation (about 15-20 mm SL) have not been described.

In this study, selected morphometric and meristic variables as well as pigment characters were examined and evaluated for their usefulness in delimiting cultured alewife and blueback herring larvae.

Methods

Alewife and blueback herring larvae were hatched from artificially-spawned eggs of known taxonomic identity and were reared to age 32 days and to age 37 days (Sismour 1994). Water temperatures in aquaria during egg incubation were approximately 17° to 20°C for alewife and approximately 19° to 22°C for blueback herring. Daytime water temperatures experienced by larvae in the outdoor tanks ranged from about 13°C to about 23°C for alewife and from about 21°C to about 28°C for blueback herring. Eggs were sampled during embryo development, and yolk-sac larvae were maintained in the aquaria and were sampled at hatching and at least once before the yolk was completely absorbed. Larvae were transferred prior to complete yolk absorption to 1-m^3 tanks in a continuous flow-through system. The system, which was located outdoors, utilized a pump to deliver water and entrained zooplankton from the Pamunkey River, Virginia, to two tanks in which larvae were reared (Sismour 1994).

Larvae were collected with a plankton net from the tanks at irregular intervals ranging from 3 to 5 days throughout their development. Captured larvae were concentrated in the cod-end jar of the net and gently poured into a small (125 mL) glass jar to facilitate observation. They were then transferred using a plastic pipet into a petri dish containing a solution of tricaine methanosulfate (MS-222). The amount of MS-222 needed to anaesthetize larvae was initially determined by placing a few larvae in the petri dish and adding small amounts of MS-222 with a laboratory microspatula until larvae stopped moving. With experience, the amount of MS-222 necessary to anaesthetize larvae was estimated without trial. No attempt was made to measure the amount of MS-222 used in the anaesthetic solution since the MS-222 concentration was diluted as larvae were transferred to the petri dish. Small amounts of MS-222 were added to the petri dish when larvae began to revive.

Standard length (SL) and snout-to-vent length (SVL; following the definitions of Lippson and Moran 1974) were measured for the anaesthetized larvae using a Wild M3Z dissection microscope with a 120-unit graduated ocular micrometer. Larvae were measured to the nearest 0.5 micrometer unit at one of three magnifications: 6.5x, 10x, or 16x. Measurements were later converted into millimeters using calibration factors determined for each magnification. Anesthetized larvae used in this study were fixed in either 5% phosphate buffered formalin (PBF) (Markle 1984) or preserved in 95% ethanol (EtOH). Formalin-fixed specimens were transferred through an increasing series of 20%, 45%, and 70% EtOH for long-term preservation (Lavenberg et al. 1983). Specimens preserved in 95% EtOH were transferred twice to fresh 95% EtOH at 24 hr intervals. Specimens were preserved in 95% EtOH in order to prevent the dissolution of otoliths.

Snout-to-vent length to standard length ratios (SVL/SL) were calculated using measurements made on anesthetized larvae to eliminate potential error caused by fixative-induced shrinkage. The number of myomeres between the dorsal fin insertion and anal fin origin (postdorsal-preanal myomere count) were enumerated using fixed and preserved specimens. Prior to formation of dorsal fin pterygiophores, the dorsal fin insertion was defined as the myomere where the posterior margin of the dorsal fin anlage joined the body. The anal fin origin was defined as the first myomere posterior to the vent.

Melanophore and xanthophore distributions and morphologies were examined to identify pigment characters of potential value for taxonomic classification of larvae. Melanophores and xanthophores were classified as contracted if they appeared as round spots, stellate if they appeared with short protrusions, or reticulate if they appeared with dendritic protrusions (Giese 1982). For yolk-sac and preflexion larvae, the term 'supracaudal' referred to the region of dorsal finfold adjacent to the tail. The odds ratio and the associated 95% confidence interval were calculated to quantify the likelihood that an alewife larva would demonstrate supracaudal pigment (Agresti 1990).

Illustrations of formalin-fixed larvae were prepared with the aid of a camera lucida. Illustrations of alewife and blueback herring postflexion larvae emphasize ontogenetic changes in pigmentation. Morphological and osteological characteristics, such as position and number of myomeres and the number and position of fin rays were illustrated as observed on specimens that were not cleared and stained.

Xanthochrome was unstable in fixed and preserved larvae. It gradually faded over several weeks in specimens fixed in 5% PBF and was rapidly extracted from specimens preserved in 95% EtOH. A method (e.g. photography) to permanently record the distribution of xanthochrome in anesthetized larvae was not available for this study.

Wild herring larvae may have been entrained in water pumped from the river and it appears likely that some wild larvae may have been introduced into the outdoor tanks despite efforts to prevent this. The continuous-flow system incorporated 300-m mesh nylon bag filters in order to remove wild fish eggs and larvae from the entrained water (Sismour 1994). Leslie and Timmins (1989) estimated that an experimental extrusion rate of 6% is theoretically possible for gizzard shad larvae retained in 250-m mesh nylon netting. Alewife, blueback herring, and gizzard shad larvae are of similar shape and size; consequently, it is probable that wild alewife, blueback herring, or gizzard shad larvae entrained in water by the system intake may have passed through the bag filters. The SVL/SL ratio differs between alewife and gizzard shad larvae, with alewife larvae characterized by a ratio less than 0.85 (Lam and Roff 1977). On the assumption that this difference delimits *Alosa* spp. and *Dorosoma* spp., only alewife and blueback herring specimens with SVL/SL ratios less than 0.85 were used to describe pigment patterns in order to minimize the possibility of confounding pigment patterns of alewife and blueback herring larvae with pigment patterns of gizzard shad larvae. Larvae were not included for the description of pigment patterns if they were considerably smaller and developmentally less advanced than other larvae collected from the outdoor tanks for any sampling date in order to minimize the inclusion of wild specimens of any species in the description of pigment patterns.

Results

Eggs and Yolk-sac Larvae

Unfertilized and fertilized eggs of alewife and blueback herring were golden yellow. Fertilized eggs of both species readily adhered to one another and initially to nylon sieves used to rinse eggs during artificial spawning. Alewife eggs remained adhered together but detached from the sieves after several hours. In contrast, blueback herring eggs were highly adhesive and remained adhered to the sieve throughout embryonic development.

Alewife and blueback herring yolk-sac larvae were transparent at hatching with average standard lengths of 3.8 mm and 3.9 mm. Pectoral fin buds and the saccular and lagenar otoliths were present in both species. The yolk of both species was segmented. Oil droplets embedded within the yolk were not observed but occurred between the yolk and the periblast. Yolk-sac larvae of both species possessed unidentified structures associated with the periblast which may be sites for oil storage (Figure 1), but the chemical composition of these structures was not determined. These structures were easier to observe in specimens preserved in 95% EtOH, which caused the yolk to dehydrate and contract away from the periblast, as compared to anesthetized or formalin-preserved specimens.

Pigment formed in both species between hatching and about 24 hr after hatching, and consisted of dermal melanophores associated with myosepta along the lateral body surface, below the pectoral-fin buds, on the nape, and occasionally on the head. The eyes of yolk-sac larvae of both species were unpigmented at hatching, except for golden to bronze pigment along the dorsal margin, and were completely pigmented by the second day after hatching. Melanophores were distributed along the ventral surface of the yolk sac and along the gut. No consistent differences in the distribution or numbers of melanophores on the ventral surface of the yolk sac were apparent between the two species. Mełanophores in the supracaudal region were observed in yolk-sac larvae of both species.

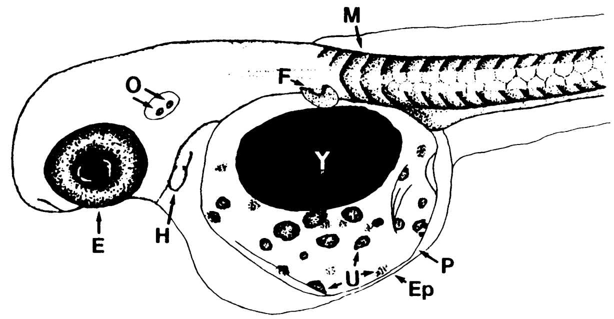

FIGURE 1.—Illustration of a 2-day old alewife yolk-sac larva emphasizing unidentified structures (U) associated with the periblast (P). Structures identified include: eye (E), heart (H), otoliths (O), yolk (Y), pectoral fin bud (F), myomeres (M), and the epiblast (Ep). The illustration was copied from a photomicrograph of a yolk-sac larvae that was fixed and preserved in 95% EtOH. The alcohol caused the yolk to dehydrate and withdraw from the membrane which facilitated observation of the unidentified structures. These structures also were observed in blueback herring yolk-sac larvae.

Meristics and Morphology of larvae

Dorsal fin anlagen were observed in alewife larvae ranging in size from 5 to 10 mm SL, and in blueback herring larvae of 7 mm SL (only 2 specimens). Within size-classes of larvae, dorsal fin pterygiophore counts were higher in blueback herring larvae than in alewife larvae up to about 12 mm SL (Table 1). Pterygiophore counts in both species were similar (alewife: 15-17; blueback herring: 16-18) in larvae ranging from 14 to 19 mm SL. Anal fin anlagen were observed in alewife larvae ranging from 9 to 13 mm SL (Table 2). In comparison, anal fins of blueback herring larvae had developed several pterygiophores by 10 mm SL (Table 2). Anal fin pterygiophores were not observed in alewife larvae until 11 to 12 mm SL. In larvae from 13 to 19 mm SL, anal fin pterygiophores ranged in number from 14 to 19 for blueback herring and from 10 to 20 for alewife (Table 2).

Sixty-four alewife larvae from 6 to 18 mm SL and 68 blueback herring larvae from 6 to 14 mm SL were examined to determine the diagnostic value of the postdorsal-preanal myomere count for identifying larvae. The postdorsal-preanal myomere count ranged from 5-11 for alewife and from 6-10 for blueback herring, and decreased in number as standard length increased (Table 3). Both species were characterized by a mode of 9 postdorsal-preanal myomeres.

Alewife larvae (n=169) from 6 to 18 mm SL had SVL/SL ratios ranging from 0.77 to 0.89 while blueback herring larvae (n=205) from 6 to 17 mm SL had SVL/SL ratios ranging from 0.77 to 0.88 (Table 4). The modal values of the SVL/SL ratio for alewife and blueback herring larvae were 0.83 and 0.84.

Pigmentation in preflexion larvae

Ventral margin and gut. A single row of melanophores appeared either as a solid or fragmented line of pigment anterior to the cleithrum. Two rows of melanophores appeared either as solid or fragmented lines of pigment posterior to the cleithrum. These rows diverged from a common origin at the cleithrum to a position between the gut and the myomeres, and ended between the 14th to 17th myomeres. Among alewife preflexion larvae, the junction of the two rows of pigment at the cleithrum had an angular appearance and the rows of pigment were relatively straight as they diverged from the cleithrum (Figure 2). Among blueback herring preflexion larvae, the rows of pigment diverged in a shallow arc and their junction at the cleithrum appeared rounded (Figure 2). These differences were consistent among some preflexion larvae with

TABLE 1.— Dorsal fin pterygiophore counts for alewife and blueback herring larvae. Table values indicate the number of larvae observed in which the dorsal fin anlagen (A) has developed or the number of larvae with the specified number of pterygiophores. SL = standard length (mm).

		Dorsal Fin Pterygiophore Number															
SL	Species	A	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
5	Blueback																
	Alewife	1	1														
6	Blueback																
	Alewife	1															
7	Blueback	2															
	Alewife	2															
8	Blueback				1	1											
	Alewife				1												
9	Blueback																
	Alewife	1					2	3									
10	Blueback										4	1	2				
	Alewife	2						1	2								
11	Blueback																
	Alewife									1	1			1			
12	Blueback												3	5	3	2	
	Alewife										1		1				
13	Blueback												1	1	6	6	3
	Alewife								1				4	1			
14	Blueback														3	4	
	Alewife													3	1		
15	Blueback															3	4
	Alewife													1			
16	Blueback																
	Alewife													3	1		
17	Blueback																2
	Alewife															4	
18	Blueback																
	Alewife															2	
19	Blueback															1	
	Alewife																

complete patterns, but the pattern was incomplete in most preflexion larvae examined. Two rows of melanophores along the ventral surface of the gut, appearing as either solid or fragmented lines of pigment, began between the 12th and 15th myomere and ended at the vent. Scattered melanophores occurred posteriorly to the vent along the ventral surface in preflexion larvae of both species. This pigmentation was maintained in postflexion larvae, but became less prominent in larger specimens.

Caudal region. Supracaudal melanophores were more frequent in alewife preflexion larvae (89%) than in blueback herring preflexion larvae (8%). The odds ratio calculated for the observed frequencies was 89.9 (95% C.I.= 40.4 to 164.0) indicating that, on average among the cultured specimens, an alewife preflexion larva was about 90 times more likely to have supracaudal pigment than a blueback herring preflexion larva. When present, these melanophores were observable until notochord flexion. After flexion, pigmentation in this region increased causing the supracaudal melanophores to become indistinct.

Pigmentation in postflexion larvae

Few melanophores were observed on preflexion larvae of either species except for melanophores associated with the gut, the posterior ventral margin, and the supracaudal region. With the onset of flexion, melanophores increased in number on the head and epaxial surface of the body, along the dorsal margin, and on the dorsal

TABLE 2.— Anal fin pterygiophore counts for alewife and blueback herring larvae. Table values indicate the number of larvae observed in which the anal fin anlagen (A) has developed or the number of larvae with the specified number of pterygiophores. SL = standard length (mm).

		Anal Fin Pterygiophore Number																	
SL	Species	A	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
9	Blueback																		
	Alewife	1																	
10	Blueback							1	1	2			2	1					
	Alewife	1																	
11	Blueback													1	1				
	Alewife	1				1													
12	Blueback											4	1	4	1		2		
	Alewife		1											1					
13	Blueback												3	4	2	7	2		
	Alewife	1							3		1			1					
14	Blueback														1	3	3		
	Alewife													2	1	1			
15	Blueback															2	4	1	
	Alewife															1			
16	Blueback																		
	Alewife														1	2		1	
17	Blueback																2		
	Alewife																3	1	
18	Blueback																		
	Alewife																	1	1
19	Blueback																		
	Alewife																	1	

TABLE 3.— Postdorsal-preanal myomere counts of alewife and blueback herring larvae. Table values indicate the number of larvae observed with the specified myomere count. SL = standard length (mm).

		Postdorsal-Preanal Myomere Count						
SL	Species	5	6	7	8	9	10	11
6	Alewife						1	
	Blueback				1	1	1	
7	Alewife					2		
	Blueback				1	7	2	
8	Alewife					1	1	
	Blueback					1	1	
9	Alewife				1	1		2
	Blueback					3	1	
10	Alewife					2	4	
	Blueback				1	4	2	
11	Alewife					1	5	1
	Blueback			1		5		
12	Alewife			1		1	4	1
	Blueback			4	5	5		
13	Alewife			2	1	10		1
	Blueback			6	7	3		
14	Alewife			1				
	Blueback		1	4	1			
15	Alewife			3		2		
	Blueback							
16	Alewife		1	2	3			
	Blueback							
17	Alewife	1	3		1			
	Blueback							
18	Alewife		2		1			
	Blueback							

TABLE 4.— Snout-to-vent length/standard length (SVL/SL) ratios for alewife and blueback herring larvae. Table values indicate the number of larvae with the specified SVL/SL ratio. SL = standard length (mm).

		Snout-to-Vent Length / Standard Length Ratio (X100)												
SL	Species	77	78	79	80	81	82	83	84	85	86	87	88	89
6	Blueback						3 10	6	5					
	Alewife				1	5		6	1	3				
7	Blueback							3	9	3				
	Alewife						5	9	5	2				
8	Blueback							2	3	1	1			
	Alewife						4	2	5	1		1		
9	Blueback						1	4 10						
	Alewife								3	3				
10	Blueback						1	7	8	3				
	Alewife						1	4	3					
11	Blueback						2	4	8	4	1	1		
	Alewife							5	6	3				
12	Blueback						1	3	13	14	4	1	1	
	Alewife						3	5	3	2	1			
13	Blueback						1	18	14	4	1			
	Alewife					1	2	2	6	3				1
14	Blueback				1	8	15	6	3		1			
	Alewife							2	3	1				
15	Blueback		1	2	3	5	1							
	Alewife						1		2					
16	Blueback					1								
	Alewife					3	2	3	1	1				
17	Blueback	1	2											
	Alewife	1		5	1		2	1						
18	Blueback													
	Alewife		5	5	2	2								

and lateral surfaces of the gut in both species. Yellow pigment was observed in anesthetized postflexion larvae; it gradually deteriorated in specimens fixed in 5% PBF after several weeks, and it was rapidly extracted from specimens preserved in 95% EtOH. The gradual fading of yellow pigment in formalin-fixed specimens and its rapid extraction in ethanol suggests that it was lipochrome and is generically known as xanthochrome. The occurrence of xanthochrome in alewife larvae was noted initially, but its distribution was not examined in detail until different xanthochrome distributions were observed in blueback herring larvae. Xanthochrome distributions of alewife larvae previously fixed in 5% PBF were then reexamined. Although xanthochrome pigment in formalin-fixed alewife larvae gradually decreased with time, observed distributions of xanthochrome were consistent between anesthetized and formalin-fixed alewife larvae. Observed xanthochrome distributions were consistent within species. Xanthochrome distributions observed in alewife and blueback herring larvae are summarized in Table 5.

Head pigmentation. Pigmentation in the head region of both species began with the development of subdermal reticulate melanophores associated

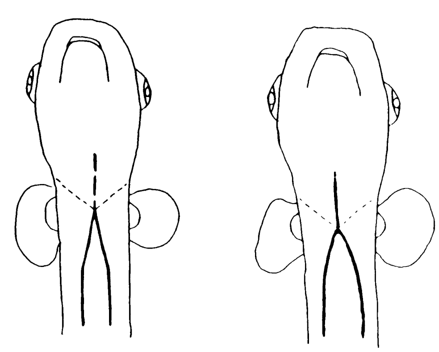

Figure 2.—Generalized ventral pigment patterns observed for alewife (left) and blueback herring (right) preflexion larvae. Most larvae examined lacked sufficient pigment to complete either pattern.

with the otic bullae and the ventral surface of the brain (Figures 3a and 4a). With increased size, dermal melanophores developed on the dorsal surface of the mandible and maxilla, on the head, and on the epaxial surface of the body in both species. Melanophores on the head of alewife postflexion larvae initially were typically contracted or stellate (Figure 5), but those on the head of blueback herring postflexion larvae typically were stellate or reticulate (Figure 6). With increased length, reticulate dermal melanophores developed on the head of larvae of both species.

Xanthophores were observed on the head of larvae in both species beginning at about 11 to 12 mm SL. Among blueback herring larvae, xanthophores on the head were relatively large and reticulate, and eventually covered the dorsal surface of the head above the brain. Beginning at about 13 mm SL, xanthic pigment was observed along the ascending process. In contrast, scattered, contracted xanthophores developed on the dorsal surface of the head of alewife larvae, and xanthochrome was not observed along the ascending process.

Dorsal mid-line and epaxial surface. Qualitative differences in the distribution and density of melanophores between the two species were most prevalent along the dorsal mid-line, especially posterior to the dorsal fin. Melanophores were initially absent along the dorsal mid-line in early postflexion larvae of both species (Figures 3a and 4a). Two parallel rows of melanophores along the posterior dorsal mid-line were observed earlier in blueback herring postflexion larvae (Figure 3b and 3c) than in alewife postflexion larvae (Figures 4b and 4c). With ontogeny, the two parallel rows of melanophores developed in blueback herring and alewife postflexion larvae extending from the nape to the caudal fin (Figures 3d and 4d, respectively). Melanophores along the dorsal mid-line were typically reticulate in both species, but they were frequently larger and more numerous in blueback herring postflexion larvae (Figure 3b to 3d) yielding an appearance of darker pigmentation than in alewife postflexion larvae of similar standard length (Figure 4b to 4d).

Xanthochrome was observed at the base of the dorsal fin and along the dorsal mid-line of blueback herring postflexion larvae beginning at about 14 mm SL, but it was not observed in these areas in alewife larvae (Table 5). Xanthophores developed on the epaxial body surface of alewife postflexion larvae beginning at about 15 mm SL, but they were not observed on the epaxial surface of blueback herring larvae.

Caudal fin. Melanophores on the caudal fin appeared to be more numerous in many blueback herring larvae, but the abundance of melanophores varied and could not be used as a trait for identifying species. On the other hand, the occurrence of

TABLE 5.— Summary of the distribution of xanthophores in cultured alewife and blueback herring larvae. 'Absent' and 'Present' denote diagnostic characters; 'Not observed' indicates that there was some uncertainty regarding the absence of the character. SL is standard length and refers to the size at which a character was first observed although not all specimens might have exhibited the character at that size.

Xanthophore distribution	Alewife	Blueback herring
Dorsal surface of head	Dermal; small, contracted or stellate; scattered; observed beginning at about 11 mm SL	Dermal; large, reticulate; covers brain; observed beginning at about 10-11 mm SL
Base of caudal fin	Absent	Present; observed beginning at about 10-11 mm SL
Epaxial surface of body	Dermal; observed beginning at about 15 mm SL	Not observed
Base of dorsal fin and along dorsal mid-line	Not observed	Dermal; observed beginning at about 14 mm SL
Nape	Dermal; small, contracted or stellate; observed beginning at about 18 mm SL	Not observed
Dorsal to vertebral column	Not observed	Internal; present initially as spots which coalesce into solid line with development; observed beginning at about 12-13 mm SL
Ventral to vertebral column	Internal; observed only in the caudal region of a single specimen, 15.6 mm SL	Internal; observed only in caudal region; observed beginning at about 12-13 mm SL
Snout	Not observed	Dermal; follows ascending process; observed beginning at about 13 mm SL

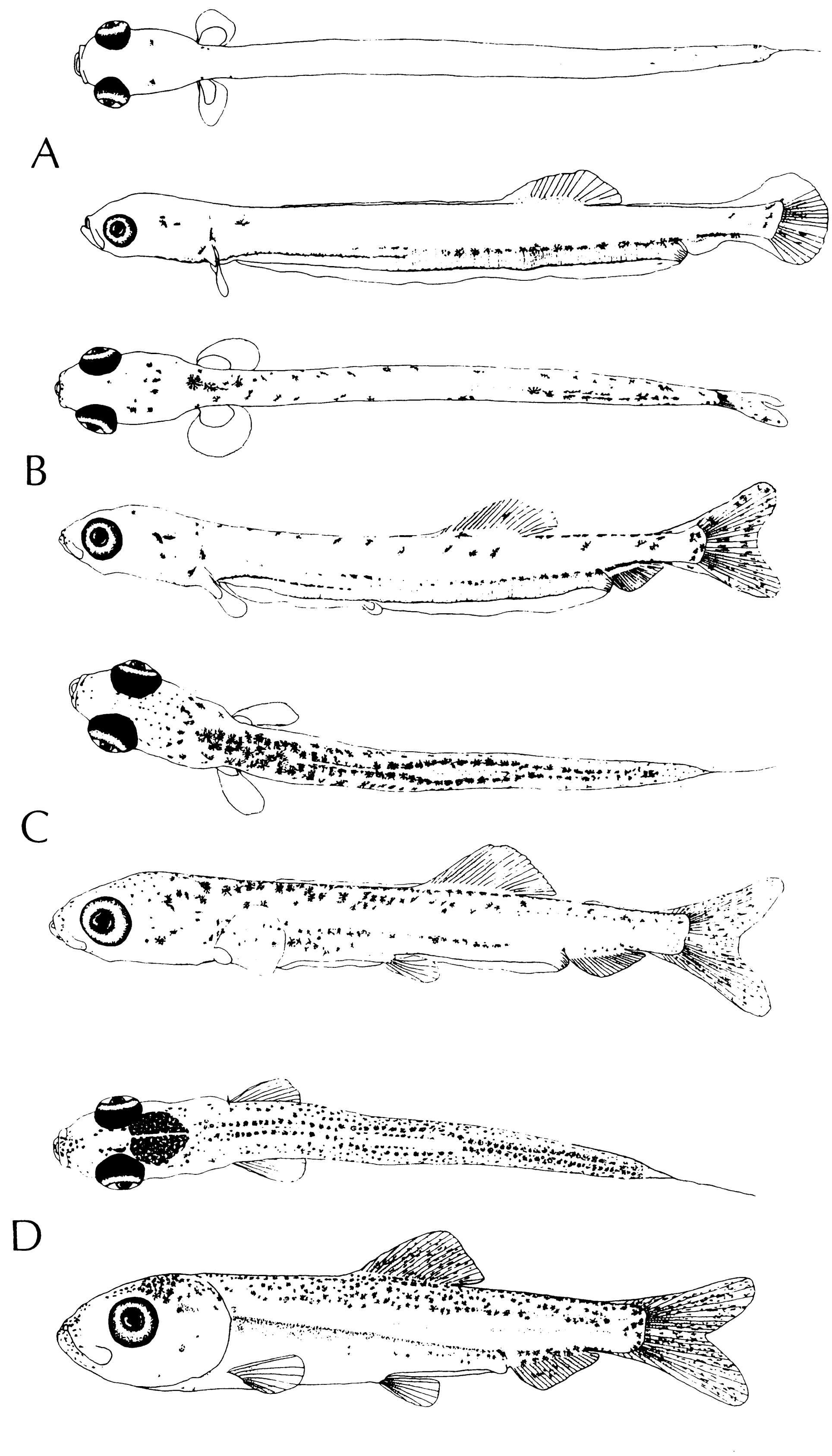

Figure 3.—Illustrations of developing blueback herring larvae (standard lengths in mm): a) 10.1; b) 11.6; c) 13.5; d) 17.1.

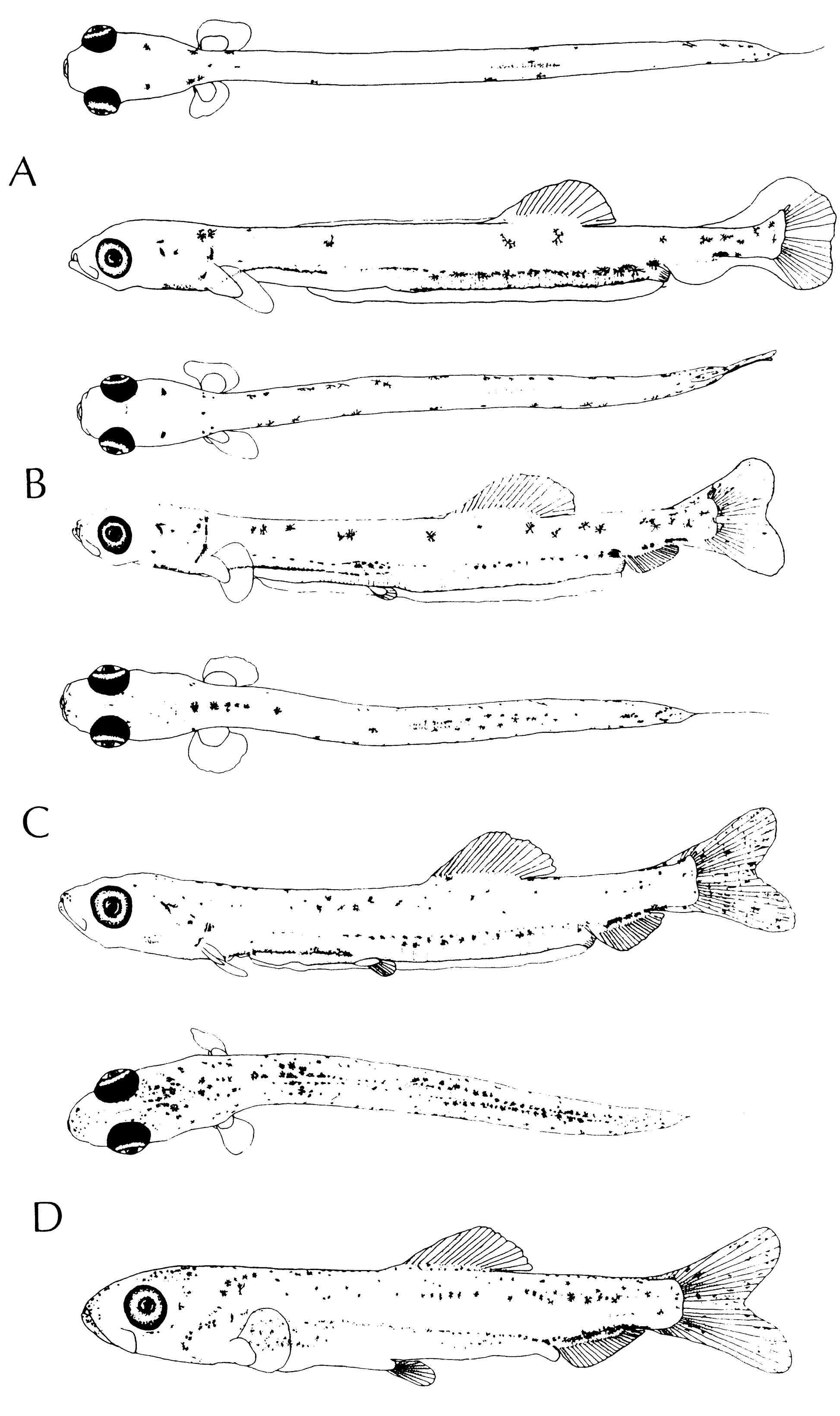

Figure 4.—Illustrations of developing alewife larvae (standard lengths in mm): a) 11.4; b)13.3; c)15.2; d) 17.8.

xanthochrome on the caudal fin was diagnostic. Xanthochrome was observed as a yellow patch at the base of the caudal fin in blueback herring postflexion larvae beginning at about 11 to 12 mm SL, but it was never observed on the caudal fin of alewife larvae.

Internal pigment. The distribution of melanophores along the notochord at the level of the nape was diagnostic for blueback herring and alewife larvae larger than 11 mm SL. In alewife larvae, melanophores developed in pairs on the lateral aspects of the notochord beginning at about 15 mm SL and increased in number with increasing length (Figure 5). From one to three pairs of melanophores occurred in most alewife postflexion larvae examined. Notochord pigment of blueback herring developed as early as 11 mm SL and appeared most often as a single, large, reticulate melanophore, but occasionally as two large, reticulate melanophores (Figure 6). Melanophores were found to be distributed along the lateral and dorsal surfaces of the notochord in specimens of both species which appeared to have been undergoing or had completed transformation to the juvenile stage.

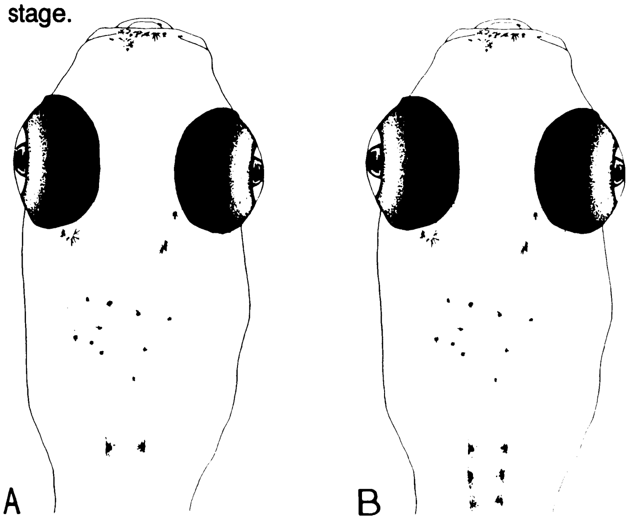

Figure 5.—Pigmentation of the head region (dermal) and notochord (internal) of alewife larvae. The number of melanophores along the lateral surface of the notochord: A) a single pair commonly was observed at about 15 mm SL, and B) 3 pairs were commonly observed at about 17 mm SL. An illustration of a single larva (15.5 mm SL) was modified to show the increase in the number of melanophores that occurred during ontogeny.

Xanthophores were observed in blueback herring postflexion larvae dorsally and ventrally to the vertebral column beginning about 13 mm SL. Xanthic pigment ventral to the notochord was observed only in a single alewife of about 16 mm SL.

Diurnal expression of xanthochrome. Xanthophores were observed in an expanded condition only during daylight hours. A small number of blueback herring postflexion larvae were sampled on one occassion at night and all lacked xanthochrome, whereas larvae of similar size sampled during the day possessed xanthochrome.

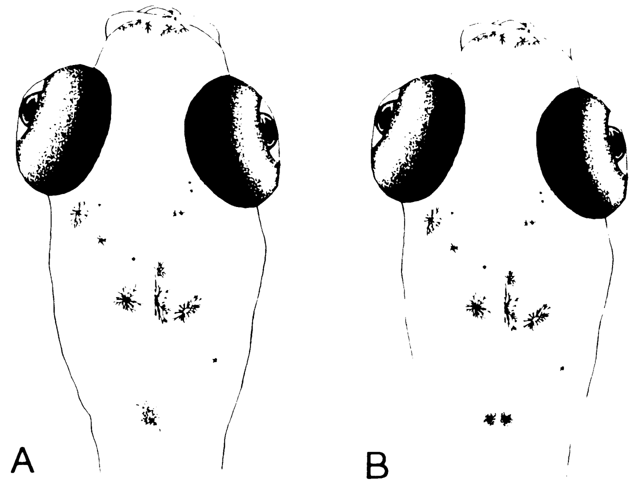

Figure 6.—Pigmentation of the head region (dermal) and notochord (internal) of blueback herring larvae. Two alternative patterns observed among specimens are illustrated: A) single melanophore pattern, and B) double melanophore pattern. The occurrence of the single and double melanophore patterns were independent of standard length. An illustration of a single larva (11.8 mm SL) was modified to show both pigment patterns.

Discussion

Meristics and morphology

Identification of the early life stages of alewife and blueback herring larvae is problematic. Eggs and yolk-sac larvae of these species observed for this study were indistinguishable. Eggs, yolk-sac larvae, and preflexion larvae of these species have been previously described and are illustrated in numerous publications (Kuntz and Radcliffe 1917; Norden 1967; Lippson and Moran 1974; Jones et al. 1978; Wang and Kernehan 1979; see also Cianci 1969). Characteristics suggested to potentially delimit alewife and blueback herring yolk-sac larvae, including the differential appearance of oil droplets (Lippson and Moran 1974), melanophore distribution on the ventral surface of the yolk sac (see descriptions in Jones et al. 1978), and eye pigmentation at hatching (Cianci 1969) were not found to differ between alewife and blueback herring yolk-sac larvae examined for this study. Other characters (e.g. biochemical traits) may be required to delimit the early life stages of these species.

The usefulness of meristic or morphologic characters for identifying alewife and blueback herring larvae had not been resolved prior to the present study. Cianci (1969) found no significant meristic or morphometric variation between alewife and blueback herring larvae reared from eggs of known taxonomic identity, and his results were confirmed by Marcy (1976). In contrast, Chambers et al. (1976) hypothesized that several meristic and morphologic characters of larvae of these species differed based on an evaluation of field-collected herring larvae sampled from locations where either gravid alewife or gravid blueback herring adults were captured in gillnets. Larvae, which they classified as blueback herring, had significantly more postdorsal-preanal myomeres and a larger SVL/SL ratio (11 to 13 myomeres and about 0.87) than larvae which they classified as alewife (7 to 9 myomeres and about 0.82; Chambers et al. 1976). The two groups of larvae also differed in the number of preanal myomeres and in the ratios of vent-to-urostyle length and vent-to-tail length to standard length (Chambers et al. 1976). All morphometric measurements used by Chambers et al. (1976) are associated with gut length such that a longer gut yields greater preanal and postdorsal-preanal myomere counts and higher SVL/SL ratios. As a result, no additional information is obtained using the ratios of vent-to-urostyle length or vent-to-tail length to standard length for identifying these species that is not provided by using the SVL/SL ratio.

Other studies do not support the hypothesis that alewife and blueback herring larvae are characterized by significant meristic or morphometric variation. Lam and Roff (1977) compared alewife larvae with gizzard shad larvae from Lake Ontario, and Bulak (1985) compared blueback herring larvae with gizzard shad and threadfin shad larvae from the Santee-Cooper River system of South Carolina. The SVL/SL ratio is the only characteristic which Lam and Roff (1977) identified which delimits alewife and gizzard shad less than 16 mm SL. According to Lam and Roff (1977), the SVL/SL ratio for larvae less than 16 mm SL ranges from 0.78 to 0.85 for alewife and from 0.85 to 0.88 for gizzard shad, and the SVL/SL ratios of alewife and gizzard shad of at least 16 mm SL ranges from 0.78 to 0.82 and from 0.75 to 0.86. Blueback herring less than 14 mm SL examined by Bulak (1985) were characterized by 11 or fewer postdorsal-preanal myomeres (range: 5-11) compared to 10 or more (range: 10-14) for gizzard shad of the same length.

Bulak (1985) suggested that Chambers et al. (1976) may have reversed the identification of their alewife and blueback herring groups. The findings of Lam and Roff (1977) and Bulak (1985), when considered together, suggest that Chambers et al. (1976) may have compared river herring larvae to gizzard shad larvae. The results of Lam and Roff (1977) and Bulak (1985) support Cianci's (1969) conclusion that morphometric and meristic characters of alewife and blueback herring larvae do not differ significantly.

The present study confirms that alewife and blueback herring larvae do not exhibit significant meristic or morphometric variation useful for delimiting field-collected specimens of these species. The frequency distributions of both the postdorsal-preanal myomere count and the SVL/SL ratio for these two species overlapped extensively so that discrimination of the two species was not possible using either of these characteristics. The results indicate that the postdorsal-preanal myomere count and the SVL/SL ratio are of little value as diagnostic traits. The percentage of alewife and blueback herring larvae with SVL/SL ratios greater than 0.85 was 1.8% and 5.3% which suggests that a small number of wild gizzard shad larvae might have been introduced from the river into the tanks of the continuous-flow system.

The ontogeny of dorsal and anal fin pterygiophores differed between alewife and blueback herring larvae examined for this study. However, it was not possible to determine whether differences in ontogeny of dorsal and anal fin pterygiophores between these species were due to variation in developmental timing or to developmental plasticity as affected by water temperature during the development of embryos and larvae since the two species were not reared simultaneously.

Pigmentation

Alewife and blueback herring preflexion larvae show the general pigmentation pattern characteristic of clupeid larvae (Russell 1976; Moser 1981) with pigment occurring at the interface of the gut and myomeres and along the ventral mid-line. Ripple et al. (1982) reported that ventral pigment patterns of field-collected preflexion herring larvae identified as alewife and blueback herring based on the criteria of Chambers et al. (1976) were highly variable and did not delimit the two groups. In the present study, slight differences in the appearance of ventral pigment were noted in a number of larvae (Figure 2). Because ventral pigment patterns were usually incomplete, these differences could not be confirmed for use in identifying preflexion larvae.

Supracaudal melanophores were present in alewife preflexion larvae from Lake Michigan (Norden 1967) and the Connecticut River (Cianci 1969). Mansueti (1956) did not mention whether supracaudal melanophores were present in alewife preflexion larvae from the upper Chesapeake Bay. Cianci (1969) noted that supracaudal melanophores were absent in blueback herring preflexion larvae from the Connecticut River. Kuntz and Radcliffe (1917) did not mention specifically whether supracaudal melanophores occurred in blueback herring preflexion larvae, but these melanophores are evident in an illustration of a preflexion larva they identified as a blueback herring (Figure 99 in Kuntz and Radcliffe 1917).

Supracaudal melanophores were observed in both alewife and blueback herring preflexion larvae examined for this study. Although more prevalent among alewife preflexion larvae, supracaudal pigment should not be used exclusively to delimit these species in field collections since it is not diagnostic and its frequency in field-collections of larvae is likely to vary. The frequency of supracaudal pigment in a group of preflexion larvae reared in 1990 from naturally-spawned eggs collected from Herring Creek, a tidal freshwater tributary or the James River, Virginia, was 29% (Sismour 1994). Alewife are not known to spawn in Herring Creek so these larvae were most likely blueback herring, and the relatively low frequency of supracaudal pigmentation supports this identification.

Pigmentation features described by Wang (1970) for older larvae and for early juveniles of alewife and blueback herring are similar to pigmentation observed among alewife and blueback herring larvae reared in this study, although some differences were noted. Wang (1970) described late-stage postflexion alewife larvae and early-stage alewife juveniles (15-20 mm SL) as having two rows of melanophores along the dorsal mid-line from the nape to the caudal peduncle as well as melanophores on the epaxial body surface. Wang (1970) also described early-stage juvenile blueback herring (20 mm SL) as having two rows of melanophores along the dorsal mid-line from the dorsal fin insertion to the caudal peduncle and lacking melanophores on the epaxial body surface. In this study, both species developed two parallel rows of pigment along the dorsal mid-line from the nape to the caudal peduncle and both developed pigment on the epaxial surface. In both regions, pigmentation was heavier in blueback herring larvae than in alewife larvae.

Several of the pigment characters analyzed for this study differed between alewife and blueback herring larvae. Pigment characters which delimited postflexion larvae developed as early as about 11 to 12 mm. Melanophore distribution on the notochord at the level of the nape was diagnostic. This diagnostic pigmentation as well as other differences in melanophore distribution or morphology, such as occurred along the dorsal mid-line posterior to the dorsal fin, and in xanthophore distribution and morphology, may assist in species identification of field-collected specimens prior to development of juvenile and adult characters.

The utility of xanthochrome distributions as diagnostic taxonomic characters for identifying wild larvae is limited by relatively rapid deterioration of xanthochrome following fixation and preservation. Xanthochrome is a generic term for a number of carotenoid-derived lipochromes, varying in color (e.g. red, yellow, or orange), which often function as oxygen free-radical scavengers and are chemically unstable (Florey 1966). Antioxidants, such as butylated hydroxytoluene (BHT), potentially facilitate the retention of xanthochrome in fixed and preserved specimens for several months (Waller and Eschmeyer 1965; Berry and Richards 1973; D. Smith, Smithsonian Institution, personal communication).

Identifying wild larvae based on reared larvae

The identification of field-collected larvae based on descriptions of reared specimens may be of some concern since reared and wild larvae often show differences which arise as a consequence of the rearing environment. Different feeding regimes, behaviors, activity levels, and rearing conditions often lead to differences in nutritional condition, chemical composition, and morphology between reared and wild larvae (Blaxter 1975; Theilacker 1980). Rearing conditions resulting in low food availability or overcrowding may lead to increased frequencies of pigment abnormalities and bitten fins, as well as to the establishment of size hierarchies in populations of reared larvae of some species (Shelbourne 1965; Blaxter 1975). The expression of variable pigment patterns between reared larvae and wild larvae may be a function of the rearing environment, especially the lighting and temperature regimes. Shelbourne (1965) suggests that chromatophore development may be a sensitive process which might be easily disrupted by conditions associated with some rearing environments.

Various studies have produced conflicting results regarding the expression of different morphologies and pigment patterns between reared and wild fishes. Laboratory-reared larvae may be more heavily pigmented and may exhibit greater meristic variation compared to wild larvae (Powles and Markle 1984). Johnson et al. (1986) found that the meristics and morphologies of hatchery-reared and wild American shad *A. sapidissima* juveniles did not differ, but hatchery-reared specimens exhibited not differ, but hatchery-reared specimens exhibited greater pigmentation compared to wild specimens (Johnson and Loesch 1983). In contrast, Lau and Shafland (1982) reported that reared and wild larval snook *Centropomis undecimalis* did not differ in morphology or pigmentation patterns, but that reared larvae might exhibit anomalous dorsal and anal fin ray counts.

In the present study, larvae were reared in outdoor tanks to minimize the effect of rearing container size on larval development and behaviour (Theilacker 1980). Rearing conditions experienced by these larvae during their development in these tanks imitated the natural environment of the Pamunkey River (Sismour 1994). Rearing conditions are suggested to have had minimal influence on pigment patterns of the reared alewife and blueback herring larvae. Pigment patterns might have been influenced to some degree by seasonal increases in temperature and lighting associated with the transition from spring to summer. Since larvae of the two species were not reared simultaneously, they did not experience precisely the same conditions during development.

Melanophores 'expand' or 'contract' as a physiologic response to environmental factors (Fujii 1969; Faber 1980; Mansfield and Mansfield 1982; Langsdale 1993) and they may also expand when larvae are anaesthetized (Langsdale 1993). Changes in the physiological state of melanophores would result in qualitative variation in relative pigmentation intensity, in relative size of melanophores, and in relative distribution of pigment. Intraspecific pigmentation variation, caused by fluctuations in the physiologic condition of melanophores, might render qualitative pigmentation differences irrelevant for species identification of larvae if intraspecific variation exceeds interspecific variation. In the present study, differences in pigment patterns involved unique distributions of melanophores on the notochord, different ontogenies of melanin pigment along the posterior dorsal mid-line, and unique distributions and ontogenies of xanthophores. The appearance of these different pigment characters was consistent among reared larvae of each species suggesting that environmentally-induced variation may not have been an important factor in determining the degree of pigmentation of larvae. This also suggests that errors due to possible contamination of collections with wild larvae was minimized.

The usefulness of diagnostic and qualitative pigment characters for identifying wild alewife and blueback herring larvae remains to be determined. I have collected herring larvae from the Pamunkey River, Virginia, which possessed the 'alewife' pigment pattern and I have seen herring larvae collected from the Rappahannock River, Virginia, (Dr. W. Wieland, Mary Washington College) which possessed the 'blueback herring' pigment pattern. These preliminary observations suggest that pigment characters identified in this study may facilitate the identification of wild alewife and blueback herring larvae.

Ecological significance of xanthic pigment

Carotenoids have various physiological roles in animals. Physiological roles of ββ-carotene, for example, include provitamin A (retinol) activity, protection against photo-oxidation and photosensitization, and modification of the immune response and melanogenesis in humans (Kornhauser et al. 1989). In addition to similar physiological roles of carotenoids in fishes, xanthochrome may have secondary functions including species recognition and predator avoidance. Unique distributions of yellow, orange, and red pigments occur in larvae of a number of marine species (Berry and Richards 1973; D. Smith, Smithsonian Institution, personal communication).

Larvae of many fish species are transparent at hatching and remain so throughout most of the larval stage as a mechanism to reduce predation risk from visual predators. At small body size, transparency enables light to pass through the body with minimal impedance, thereby reducing contrast with background illumination. With ontogeny, the opacity of larvae increases due to increased size and pigmentation of the eyes, increased complexity of the internal body structure, increased path-length of light through the body, the proliferation of melanophores, and the amount of food in the gut (Langsdale 1993). Increased opacity enables visual predators to detect potential prey, and strategies to offset increased visibility would be advantageous for larval clupeids. The proliferation of melanophores to reduce the body area available to refract or reflect light may reduce the stimulus to visual predators of larval fishes (Moser 1981; Langsdale 1993). The development and proliferation of xanthophores may be an analogous strategy of larvae to reduce visibility, especially in turbid, coastal waters where yellow light is the least attenuated component of the visible light spectrum (Pickard and Emery 1982). This suggests that unique xanthophore distributions may be useful for delimiting larvae of other morphologically similar species in these ecosystems.

Pigment as an aid for identifying clupeid larvae

Pigment patterns have been suggested to be of little value for identifying larvae of clupeid species (Russell 1976). However, pigment patterns may aid in the identification of larvae of some species groups prior to development of complete osteological characteristics or when meristic and morphometric characters overlap (Hettler 1984; Kendall et al. 1984). This study suggests that pigment characters can delimit postflexion larvae of two closely related clupeid species, and supports the use of pigment characters as valid taxonomic criteria for delimiting species of postflexion clupeid larvae. Further studies are necessary in order to determine the significance of pigment characters as taxonomic criteria for identifying field-collected larvae of other clupeid species.

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Reducing Entrainment of Juvenile American Shad Using a Strobe Light Diversion System

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Abstract.—An Electric Power Research Institute review of fish protection systems for hydroelectric facilities identified strobe lights as a potential system that could be used to minimize fish entrainment by modifying fish behavior. Juvenile shad accumulate in large numbers in the forebay of Metropolitan Edison's York Haven Hydroelectric Project on the Susquehanna River during their fall migration. Since 1988, studies have indicated that raft-mounted strobe lights can exclude shad from the area in front of the trashracks and bypass the shad through a sluiceway into the tailrace. Scanning sonar and tailrace and sluiceway netting were used to monitor the effectiveness of the strobe lights. Although Unit outages and river flooding limited a full evaluation in some years of the study, the strobe lights induced rapid passage of large numbers of American shad through the sluiceway with little passage through the turbines: during the 1991 tests, approximately 243,000 American shad were diverted through the sluiceway while only 15,000 passed through the hydroelectric unit closest to the area of dense fish aggregation.

The Electric Power Research Institute (EPRI) assessment of downstream migrant fish protection technologies for hydroelectric projects (EPRI 1986) indicated that many of the existing fish diversion/protection systems successfully developed for steam-generated electric facilities were too costly (per unit flow or per MW capacity) to be transferable to hydroelectric intake applications. One recommendation of the EPRI assessment was for further research on behavioral diversion systems, including strobe lights.

A number of devices have been developed which are designed to alter or take advantage of the natural behavior patterns of fish in such a way that they will avoid, or be deterred from, an intake flow. These devices, commonly referred to as behavioral barriers, include electrical screens, air bubble curtains, hanging chains, lights, sound, water jet curtains, chemicals, visual keys, and combinations of these. Recent advances in the technology and application of these systems has resulted in widespread testing at locations throughout North America (Anderson et al. 1988; Hilgert 1992; Kynard and Leary 1990; Loeffelman et al. 1991; McKinley et al. 1988; Patrick et al. 1985; Puckett and Anderson 1987).

In 1988, EPRI, Metropolitan Edison Company (Met-Ed), and the Susquehanna River Anadromous Fish Restoration Committee co-funded a study of strobe and mercury lights for diverting outmigrating juvenile American shad *Alosa sapidissima* at Met-Ed's York Haven Hydroelectric Project on the Susquehanna River. The objective of that study was to determine whether these devices could be used to divert shad away from the plant turbines and through an existing trash sluiceway near the downstream-most unit. The results of the 1988 study (Taft 1989; EPRI 1990) demonstrated that strobe lights repelled the juvenile shad and directed them through the sluiceway.

A large-scale study was conducted from 1989 through 1991 in which strobe lights were positioned in front of Units 1 through 6 (Martin and Sullivan 1992). The purpose of the study was to provide a full-scale demonstration of the effectiveness of a strobe light system in guiding downstream migrating shad past the turbine intakes to a trash sluice bypass at York Haven.

Study Site

The York Haven Project is located at river mile 52 and is the fourth dam upstream that migrating anadromous fish must pass and the first impoundment outmigrating juvenile fish must pass. The plant is located on the west bank of the Susquehanna River and has an 8,000 foot-long dam angling upstream to the east bank (Figure 1). The powerhouse consists of six Kaplan and 14 Francis turbines, each capable of passing about 800 ft^3/s. The station is capable of generating 19.6 mw from a hydraulic head of 23 feet. The corner of the

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forebay between the powerhouse and the cableway contains a gate which is typically used to sluice floating debris past the plant. Water velocities typically range from 1 to 2 feet per second (ft/s) approaching the trashracks with full unit operation, increasing to 3 ft/s immediately in front of the trashracks. During the shad outmigration period (late September to early November), river flows are typically low enough that most of the river water passes through the powerhouse, usually through Units 1 through 10. Because of the oblique angle of the dam and powerhouse relative to the water flow, shad tend to congregate in dense masses in the most downstream reach of the river near the sluiceway. The plant design and orientation probably contribute to the dense concentrations of shad.

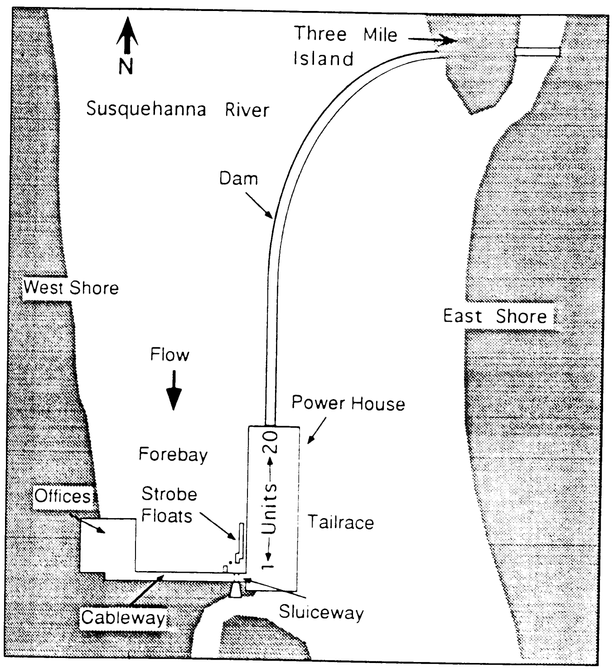

FIGURE 1.—Site diagram of the York Haven Hydroelectric Project on the Susquehanna River, Pennsylvania.

Methods

Description of the Strobe Light System

The positions of strobe lights in the forebay for the 1989 -1991 studies are shown in Figure 2. The system consisted of six floats anchored upstream of the trashrack between the cableway and Unit 6. In 1991, float 6 was placed next to the cableway about 50 feet from the sluiceway. This was done specifically to reduce the upstream escapement of fish which had been observed in previous test years. The strobe lights were attached to steel poles, and these assemblies were mounted on the floats. Each pole supported two lights: the lights were located 3 ft and 9 ft below the water surface. The poles on Floats 3 through 6 were spaced at 12 ft intervals parallel to the trashracks. The light flashheads were aimed into the flow while those on float 6 in 1991 were aimed toward the trashrack and sluiceway. The horizontal and vertical spacing was selected based on the beam spread of the lights and was designed to create a continuous "wall" of light across Units 2 through 6.

Lights on the floats closest to Unit 1 (floats 1 and 2 in 1989 and 1990; floats 1, 2, and 6 in 1991) were oriented to flash in the direction of the sluiceway. In addition, a small, moveable float supporting a single pole with two lights was positioned in a variety of locations between float 1 and the powerhouse cableway to augment and more effectively direct the repulsion of fish through the sluiceway.

The strobe light system was configured and operated as two separate arrays: the lights located on the upstream floats in front of the trashracks were operated together and sequenced by one controller; the lights located near the sluiceway were operated together by a different controller. This design allowed the upstream-oriented strobes to operate continuously to divert shad from this area and to further encourage shad to congregate in the dark area near the sluiceway. This area was kept dark most of the time (approximately 55 out of 60 minutes) during each night of testing to encourage fish to congregate there. The sluiceway gate was opened periodically (roughly once each hour) and the strobes aimed at the sluiceway were activated to repel fish through the sluiceway.

In 1992, funded solely by Met-Ed, the strobe lights and float system were re-designed to eliminate problems of leakage and to reduce their size and weight. Four of the re-designed floats (Figure 3) were arranged in an arc around the sluiceway opening with none positioned along the trashracks. Two strobe lights were suspended on a steel pole at depths of 3 and 9 feet underneath each of the floats. The floats were anchored in position (Figure 4) and had interconnecting lines to make minor adjustments in the orientation of the lights. This configuration was similar to that used in the sluiceway area in 1991 (Figure 2).

The strobe lights operated on 120 volt, 60 hertz, 20 amp service. The redesigned lights used in 1992 weighed approximately 6 pounds each and were approximately 8 x 8 x 8 inches in size. The lights were waterproof to a depth of at least 60 feet. The light output was a circular pattern, approximately 100 degrees to the 100 candela-seconds contour. The minimum peak output was 1000 candela-sec-

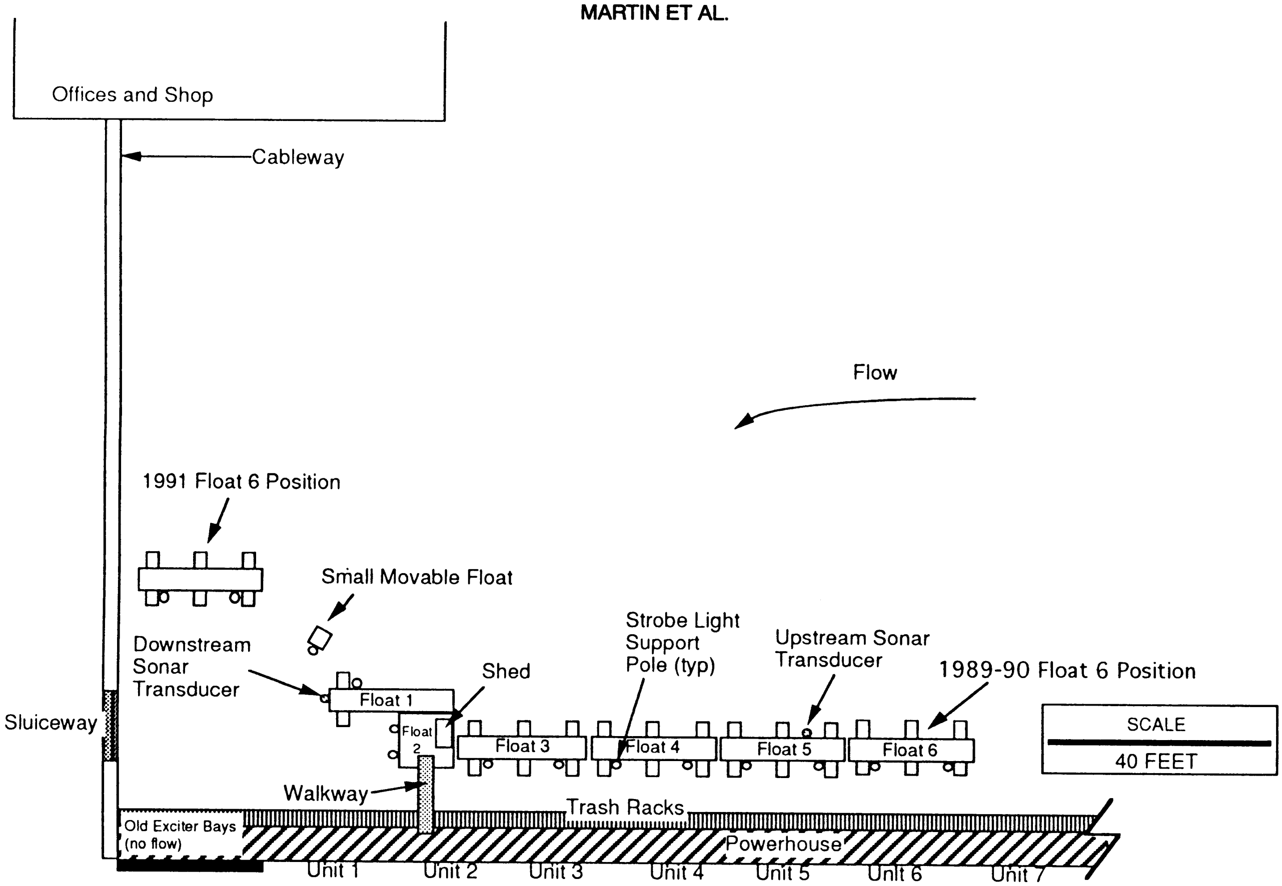

FIGURE 2.—Schematic diagram of the York Haven forebay showing the positions of strobe light floats used in 1989-1991.

onds. The power supply for each light was enclosed in a weather-tight stainless steel box, approximately 10 x 18 x 24 inches and weighed about 50 pounds. The lights were operated at a flashrate of 300/minute, providing a guaranteed life of 10 million flashes with a design life of 20 to 30 million flashes.

Scanning Sonar

The primary means of demonstrating the effectiveness of the system was through scanning sonar sampling near the trashracks and sluiceway. WESMAR Model SS390 scanning sonar units were used to monitor fish behavior and response to the strobe lights. The sonar was connected to a time-lapse video recorder and color video monitor with data recorded in VHS format. One sonar unit was deployed (range set at 50 ft) to monitor fish in the area of Unit 1 and the sluiceway. When a second sonar unit was deployed, it was located in front of Unit 5 (set at a range of 150 ft) to monitor fish as they entered the forebay area and approached the strobe light system. The sonar units were set and calibrated to achieve optimal detection and coverage of the fish.

Netting

A netting program was implemented in 1991 to quantify the passage of fish through the turbines and sluiceway under various test conditions. The sluiceway and tailrace nets used in 1991 and 1992 are shown in Figures 5 and 6. Both net frames were 39 inches square and had nets with a 0.5-inch mesh body and 0.3-inch mesh cod-end liner. The nets were 14 feet long. The tailrace net sampled 4% of the Unit 1 flow (area of net opening divided by area of draft tube exit). In 1991, the opening of the sluice net was modified to reduce the number of fish collected and injured. The 39 inch square opening was reduced to a 4 inch wide by 39 inch high opening. The modified sluice net sampled 2.8% of the sluice flow (area of net opening divided by area of sluice opening with water depth taken into account). In 1992, the sluice net sampled 33% of the flow and was used fully open because fewer fish were present.

Sampling Design

In 1989 and 1990, testing within each sample day consisted of performing control and test sequences from around dusk (approximately 1800 h) to as late as 0300 h, depending on fish abundance. The order of testing varied from night to night but included the following conditions:

- CONTROL: all lights off; sluice gate closed.
- UPSTREAM LIGHTS ON: strobe lights on floats 3 through 6 activated; downstream lights off; sluice gate closed.
- UPSTREAM AND DOWNSTREAM LIGHTS ON: sluice gate open.

For each test, the downstream scanning sonar unit was set at one of several transducer scanning angles. Additionally, an observer was positioned at the downstream side of the sluiceway opening to visually evaluate the number and behavior of fish passing out of the sluiceway. In 1989, one scanning sonar unit was deployed in mid-September to monitor fish occurrence in the forebay area. Strobe evaluation sampling began October 11 and continued until October 21 when the number of fish targets was high. In 1990, strobe evaluation sampling began on September 26 and 115 tests were conducted over the 26 days of the sampling period.

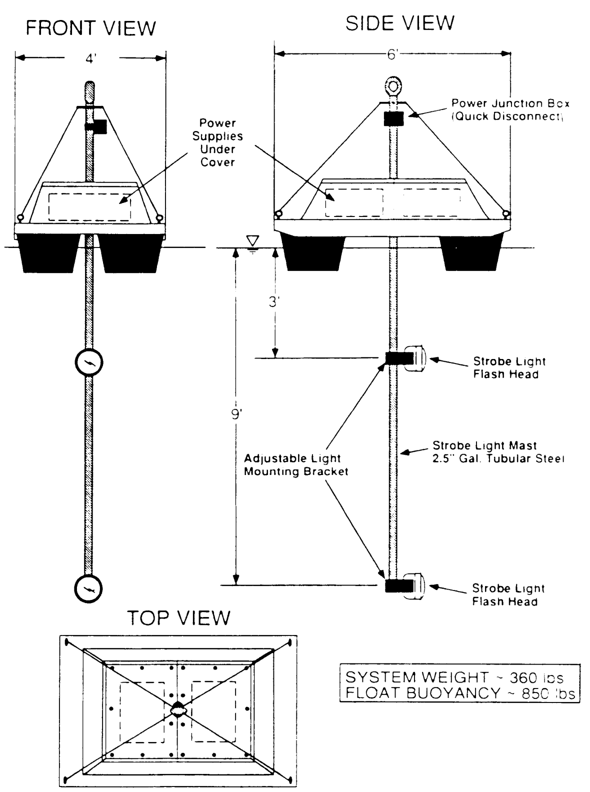

FIGURE 3.—Schematic diagrams of the modified strobe light and float assembly used in 1992.

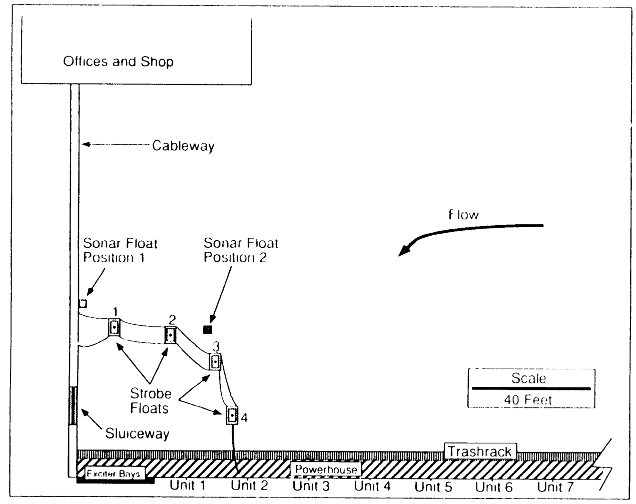

FIGURE 4.—Schematic diagram of the York Haven forebay showing the positions of strobe light floats used in 1992.

Sampling in 1991 consisted of running sequential control and test conditions from approximately dusk to dawn throughout most of the outmigration period. The field evaluation occurred between September 29 and October 27 resulting in 155 strobe light tests. The upstream strobe lights (floats 3-5) were operated continuously over the entire testing period each night to minimize turbine passage at these units and enhance congregation of fish in the area of the sluiceway. The test sequence was comprised of a control test in which the sluice gate was opened without the downstream strobes operating, and a strobe test in which the sluice gate was opened and the downstream strobes were activated. Between the tests there was a tailrace netting period to assess ambient rates of turbine passage through Unit 1. Ambient netting was performed prior to the strobe tests to ensure that a large number of fish would be in the vicinity of Unit 1 and the sluiceway and therefore would be susceptible to diversion through the sluiceway.

The following sequence of tests was repeated from six to eight times in each night:

- CONTROL: sluice gate open for two minutes (downstream strobes off); sluice and tailrace nets retrieved and re-deployed at the end of the test.
- STROBE: sluice gate open for one minute before strobes are turned on; strobe lights then illuminated for one minute; strobe lights

off and sluice gate closed (this timing resulted in the sluice gate being opened for a total of two minutes); sluice and tailrace nets retrieved at the end of the test.

- LONG-TERM TAILRACE NETTING: sluice gate closed and downstream strobes (floats 1, 2, and 6) off; tailrace net fished for one hour before retrieval and re-deployment.

In 1992, two types of tests were performed: the first 11 tests were to confirm the proper functioning of the new strobe system and to document the avoidance response of the shad; and 12 tests were performed with the tailrace and sluiceway nets in place. The testing sequence was similar to that followed in 1991 except that the sluiceway control period (sluice gate open and lights off) was not included because of the very low numbers of fish collected in this part of the test in 1991.

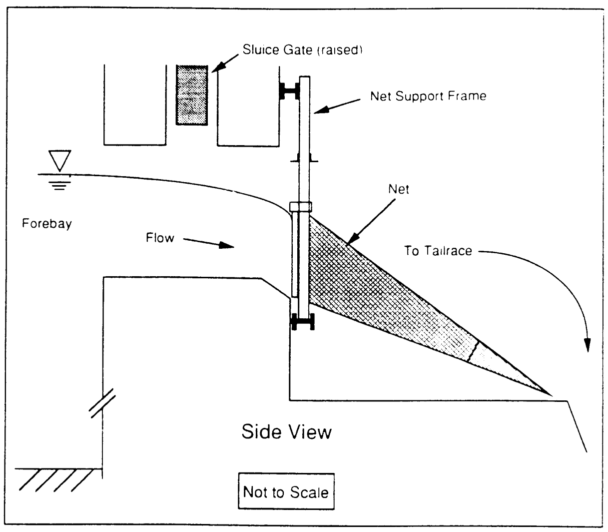

FIGURE 5.—Schematic diagram of the York Haven forebay showing the sluiceway net in sampling position (1991-1992).

Results

The 1989 results demonstrated an avoidance response by shad, although flooding and unit outages resulted in limited qualitative data. The avoidance response was indicated when shad were observed passing through the sluiceway immediately after the downstream strobe lights were activated. In addition, shad were also observed, via the sonar, traveling upstream away from the lights.

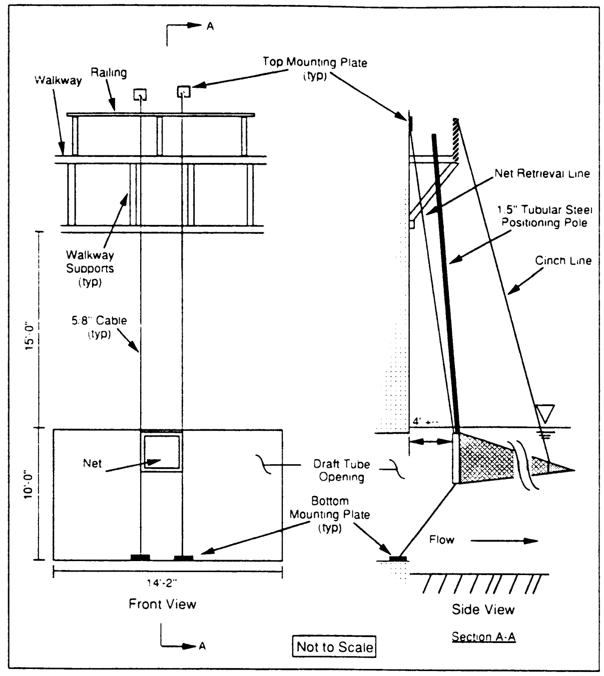

FIGURE 6.—Schematic diagram of the tailrace net in sampling position (1991-1992).

Rising water levels and high turbidity greatly reduced both the density of shad in the forebay and the effective range of the strobes. It is presumed that, as water began to flow over the crest of the dam, most of the outmigrating shad bypassed the forebay and turbines and went over the dam. This presumption is supported by the sonar data which showed fish present prior to the elevated water levels and very few fish in the forebay during and after the high water. Subsequently, testing was ended when water levels dropped without an increase in the number of shad.

Shad abundance in 1990 in the forebay was high; however, the shad did not appear to be actively migrating. Unlike in the previous two years, fish were observed in the forebay during the day as well as at night and were deeper in the water column (greater than 6 feet). The scanning sonar observations revealed shad "milling" in the forebay in a wide area upstream of the trashracks. In previous years, the sonar showed the shad in tight, active schools immediately in front of the trashracks.

An avoidance response was found in all tests in 1990; however, the fish were not observed passing out of the sluiceway in large numbers. The sonar did indicate that shad were frequently moving upstream along the cableway after strobe illumination. The sonar data indicated that the strobe lights continued to create a strong avoidance response in juvenile shad whether or not they were migrating.

In 1991, large masses of fish moved downstream through the gate when the downstream strobe lights were activated. Scanning sonar observations indicated that the predominant movement of shad was downstream, probably because the strobe lights on Float 6 cut off the escape route which had been available in previous years. The average calculated number of American shad passing through the sluiceway per test (based on netting) was 49 for control conditions and 1712 for strobe conditions. For Unit 1, the values were 5 shad under control conditions and 106 under strobe conditions. Thus more fish passed through the sluiceway with the strobes on than when the strobes were off. The strobe lights induced nearly all of the shad to pass through the sluicegate, assuming no fish passed through upstream Units 2 through 5. This assumption appears valid since the upstream strobe lights were operating at all times and shad were not observed passing through these upstream units visually or on the sonar. The estimated cumulative number of fish that passed through the sluiceway and the Unit 1 tailrace over the 24 days of testing is shown in Figure 7. Periods of no fish passage appear as horizontal sections of the plot while periods of abundant fish passage appear as steeply sloped sections. The figure clearly indicates the overwhelming number of shad that passed through the sluiceway as opposed to through Unit 1. Furthermore, comparison of the control to the strobe tests for the sluiceway revealed the necessity for the use of strobes lights (as opposed to only opening the gate) in order to effectively bypass the juvenile shad.

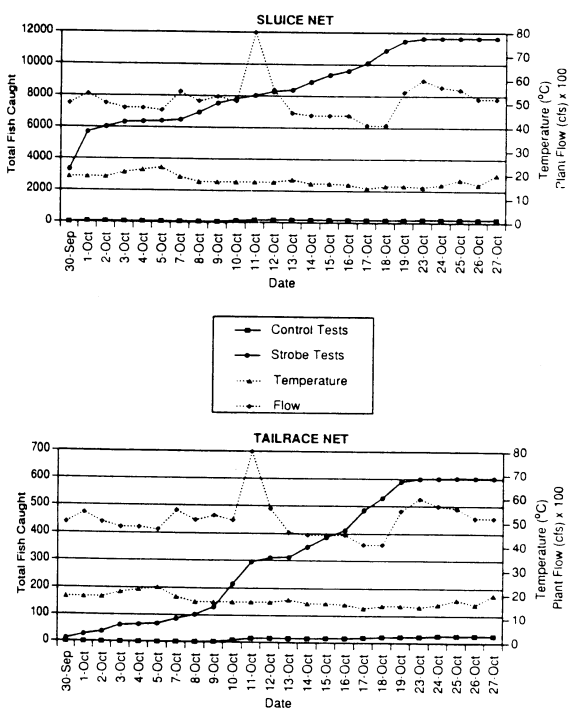

FIGURE 7.—The estimated cumulative number of fish that passed through the sluiceway and the Unit 1 tailrace from 30 September to 27 October, 1991 (cfs = cubic feet per second).

The average number of fish that passed out of the sluiceway and tailrace during different times of the night is shown in Figure 8. There is an apparent trend of minimal fish passage prior to 1800 h. Maximum fish passage occurred during early night with a gradual tapering off toward morning. Peak shad passage occurred at 2000 h. Figure 9 shows the inter-test periods of tailrace netting when only the upstream strobe lights were turned on. During these periods, it is evident that passage through Unit 1 was minimal: an average of about 50 shad per hour adjusted for the entire flow volume.

Redesigned strobe system

Although fewer fish were available for testing in 1992 compared to 1991, the response of the shad, monitored on the sonar and visually in the sluiceway, was similar. The masses of fish observed in front of the sluiceway before each test were completely repelled out of the illuminated area. No fish were observed on the sonar moving upstream past the strobe light array.

The average calculated number of fish passed during each test was 521 shad in the sluiceway net, 60 shad in the tailrace net, and 2 shad in the ambient tailrace netting. The numbers of fish passed were lower overall than in 1991 due to the limited fish abundance. However, the relative numbers of fish collected under each condition were fairly similar. It was not possible to make direct comparisons between the 1991 and 1992 data because of differences in the number of units operating, river flow level, water releases over the dam, and lower shad abundance.

Conclusions

This study demonstrated that submerged strobe lights created a strong and repeatable avoidance response in outmigrating juvenile American shad. The lights effectively repelled fish through the sluiceway with only a small proportion of the fish passing through the turbines. The avoidance response to the strobe lights lasted as long as the lights were activated and there was no evidence of fish acclimation to the light even after many hours of operation. It is possible to repel American shad from the face of the trashracks as well as to induce pas-

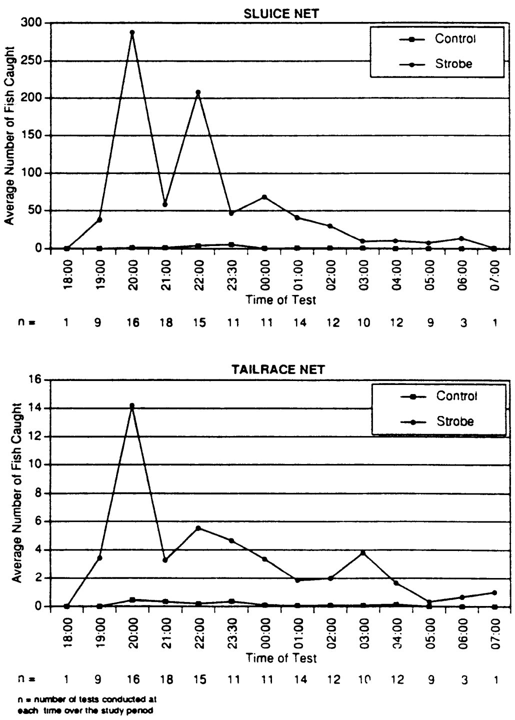

FIGURE 8.—Average number of fish caught at night in the sluiceway net and Unit 1 tailrace net from 30 September to 27 October, 1991.

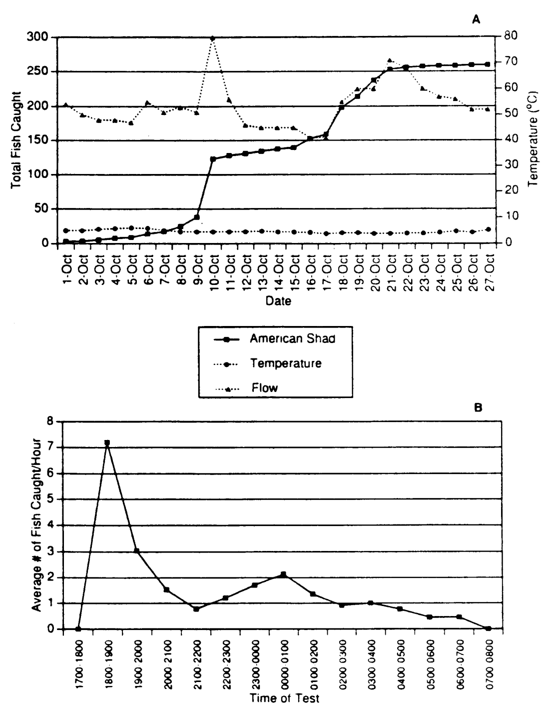

FIGURE 9.—Capture of American shad in the tailrace net with only the upstream strobe lights on. Total fish caught (A) in relation to water temperature and water flow (cfs = cubic feet per second); and (B) average number of fish caught per hour during different time periods.

sage of shad through the trash sluiceway under normal river conditions. Year-to-year variations in riverine and climatic conditions caused variations in shad migration and behavior which, in turn, influenced the number of fish passed through the sluiceway.

In two years of the study, high flows resulted in most fish passing over the dam. It is anticipated that future use of strobe lights at York Haven will demonstrate that properly arranged strobe lights will induce shad to bypass through the sluiceway and not pass through the trashracks. Strobe lights have proven to be an acceptable and cost-effective means for preventing turbine passage by migrating juvenile American shad.

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Blueback Herring Distribution and Relative Abundance in the Santee-Cooper System: Before and After Rediversion[1]

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Abstract.—Distribution and relative abundance of blueback herring *Alosa aestivalis* in the Santee-Cooper System were compared before and after rediversion of 70% of the discharge from the Cooper River to the Santee River. Changes in hydrological conditions associated with rediversion were used to explain differences in distribution and the relative abundance of blueback herring. In the Cooper River, the number of sites and length of waterways used by blueback herring increased with rediversion whereas the distribution of herring in the Santee River was similar before and after rediversion. Estimates of herring egg relative abundance (eggs/m^2/day) in Mulberry Ricefield and the Cooper River indicated a 99.6% decline in relative abundance with rediversion. Overall, the mean relative abundance of larval herring (larvae/100 m^3) in the Santee River was not statistically different before and after rediversion. However, an important historic spawning site in the Santee River contained fewer larval blueback herring after rediversion. The canal used to divert water flow to the Santee River now serves as an important spawning habitat.

In the late 1930's, Wilson Dam and Pinopolis Dam were built on the Santee River and Cooper River (U.S. Army Corps of Engineers 1975). Water from the Santee River filled Lake Marion (40,500 hectares) and the excess, about 462 m^3/s of the average annual discharge, was diverted through a 12-km canal into Lake Moultrie (27,000 hectares) and out through a 132 MW hydroelectric facility at Pinopolis Dam into the Cooper River (Figure 1). This area is known collectively as the Santee-Cooper System.

From 1980 to 1984, the navigation lock at Pinopolis Dam passed an annual average of 5.7 million fish into Lake Moultrie and Lake Marion (Cooke and Eversole 1994). Blueback herring *Alosa aestivalis* composed 97% of the fish counted (Curtis 1977). Herring serve as important prey for striped bass *Morone saxatilis* in South Carolina (Stevens 1957) and help support the landlocked population of striped bass in Lake Moultrie and Lake Marion, a sport fishery which has gained national recognition (Cooke 1990). Blueback herring have also supported a live- and cut-bait fishery within the lakes and rivers of the Santee-Cooper System.

The additional discharge in the Cooper River increased shoaling and the costs associated with ship channel maintenance in Charleston Harbor to such an extent that a second diversion project was proposed for the Santee-Cooper System. This project proposed to reduce the discharge in the Cooper River by diverting about 70% of the water through a new 14-km rediversion canal to the Santee River (Figure 1). The project included an 84 MW peak hydroelectric plant and a fish passage facility on the Rediversion Canal at St. Stephen Dam. The fish passage facility was added because Wilson Dam did not have this capability (Chappelear and Cooke 1994).

Concern was expressed that decreased discharges would adversely impact the Cooper River fishery resources. The environmental impact statement stated, however, that since the fishery "resources are directly related to the discharge and overflow characteristics," the resource "will therefore be decreased in the Cooper River and increased in the Santee River" (U.S. Army Corps of Engineers 1975). Our paper addresses this assertion by examining blueback herring distribution and estimates of relative abundance of herring eggs and larvae before and after rediversion.

Methods

Study area

In the Cooper River, our analyses concentrated on the West Branch, its tributaries, and formerly impounded ricefields along the river. The West

[1]Technical contribution No. 3390 of the SC Agriculture Experiment Station

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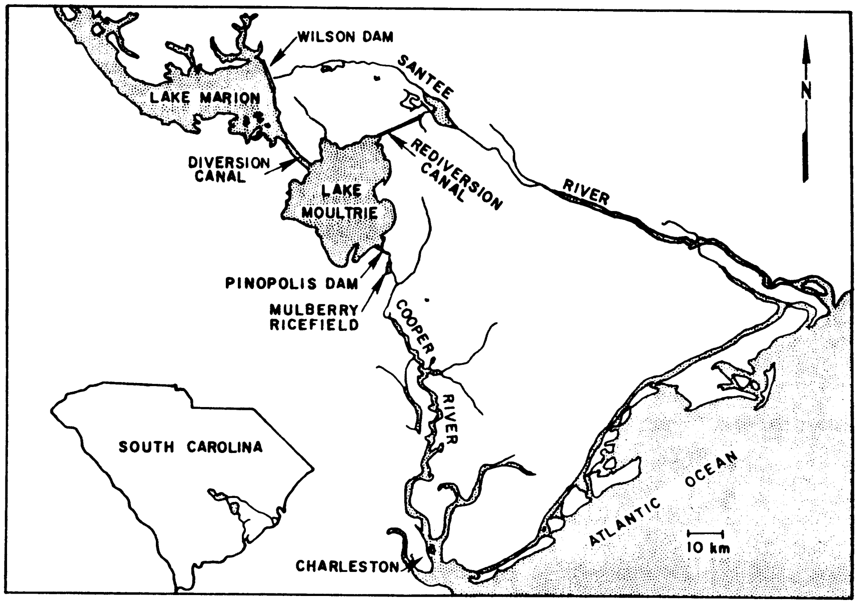

FIGURE 1.— Map of Santee-Cooper River system showing the position of the diversion and rediversion canals.

Branch extends from Pinopolis Dam (river km 77) to its confluence with the East Branch at river km 47 to form the Cooper River (Figure 1). The West Branch will be referred to hereafter as the Cooper River.

The Cooper River is relatively deep (1-20 m) and wide (91-304 m: Christie et al. 1981). The river is bordered by 2,430 hectares of formerly impounded ricefields (Christie et al. 1981; Osteen et al. 1989). Mulberry Ricefield is a typical ricefield with breached dikes and access to the main river channel. The main tributary in the study area is Wadboo Creek (Figure 2). Water levels and flow in the Cooper River are influenced by tides and discharges from Pinopolis Dam. During the spawning season (February-May), the discharge from Pinopolis Dam averaged about 422 m^3/s for the three-year study period (1978, 1981-82) prior to rediversion (Christie et al. 1981; Osteen 1985) and 128 m^3/s after (1986-89) rediversion (Slack 1991; Thomas 1990). The discharge pattern of Pinopolis Dam changed from a continuous mode of operation before rediversion to a peaking mode with substantial periods of no discharge after rediversion (Cooke and Eversole 1994).

Sampling sites on the Santee River were located from Wilson Dam (river km 140) to river km 24 where the river divides into two channels, North and South Santee rivers (Figure 3). Main river channel depths ranged from 1 to 7 m and widths from 50 to 91 m in the study area (Christie et al. 1981). The Santee River courses through an extensive forested floodplain of cypress and oak. Wambaw Creek, one of the main tributaries, drains forested wetlands characteristic of the floodplain.

Before rediversion, Santee River discharges were controlled at Wilson Dam by flood spillage gates and a small hydroelectric facility (1.5 MW). When flood gates were closed, the hydroelectric facility provided a constant 15 m^3/s discharge (Meador et al. 1984). Discharges from Wilson Dam (hydroelectric generation and flood releases) before rediversion (1978, 1981-84) averaged 223 m^3/s during the spawning season (Christie et al. 1981; Meador 1982; West 1984). There were flood releases in four of these five study years. Wilson Dam hydroelectric facility continued to operate after rediversion and the additional flow down the Santee River was channeled through the Rediversion Canal and out the new peaking hydroelectric facility at St. Stephen Dam. The average discharges from Wilson Dam and St. Stephen Dam after rediversion (1986-89) were 49 m^3/s and 295 m^3/s (Kempton 1990; Thomason 1991). Flood spillage at Wilson Dam occurred in only one (1987) of the four seasons studied after rediversion.

Distribution of herring

Extensive sampling surveys were carried out in both rivers to determine the distribution of blueback herring. Christie et al. (1981) sampled 40 sites in tributaries, ricefields, and the main channel of the Cooper River and 37 sites in tributaries and the main channel of the Santee River before rediversion. After rediversion, 35 sites were sampled in the Cooper River (Slack 1991) and 32 sites in the Santee River (Thomason 1991).

Adult blueback herring were sampled with stationary gill nets (3.18-cm bar mesh) in tributaries and ricefields, and with drifting gill nets at the main river channel sites. Stationary gill nets were fished overnight and drifting gill nets for 30 min sets. After an adult herring was caught at a ricefield and tributary site, a stationary egg net (0.5-m diameter) was set for 30 min. In those tributaries where eggs, larval or adult herring were captured, other sites upstream were sampled to determine the extent of herring distribution. Sampling to determine the relative abundance of blueback herring eggs and larvae was included in the distribution data. This sampling added one post-rediversion river site in the Cooper River (Thomas et al. 1992) and five sites before and one site after rediversion in the Santee River (Meador et al. 1984; West et al. 1988; Kempton 1990).

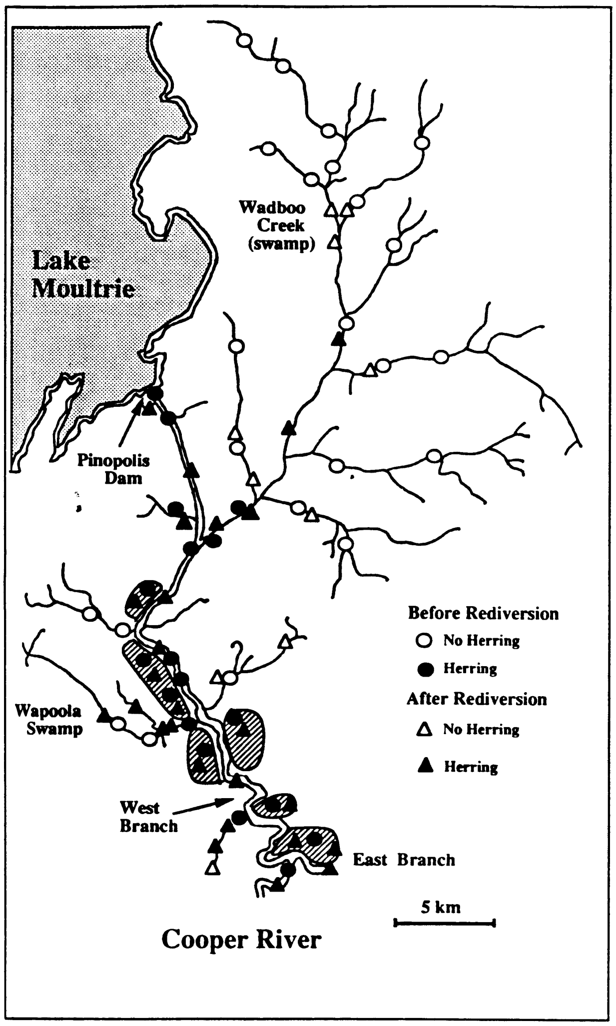

FIGURE 2.— Study section of the Cooper River.

Relative abundance

Blueback herring eggs were sampled in a portion of Mulberry Ricefield (44.5 ha) and the littoral area of the adjacent Cooper River before (1981-82) and after (1988-89) rediversion (Osteen et al. 1989; Thomas et al. 1992). The passive sampler described by Osteen et al. (1989) was used to capture herring eggs in the dense aquatic vegetation of these sample sites. Samplers were deployed at 25 stations in the ricefield and 10 in the river. Sampling stations were randomly located at the beginning of each sample season. Five more egg samplers were deployed in the ricefield in 1981; otherwise, the sampling procedures were the same before and after rediversion. Samplers were set out in late February and checked every other day through April. Each sampler effectively sampled 0.14 m^2 of surface water. The number of blueback herring eggs per sampler was used with sample area and set time in hours to calculate catch per unit effort (CPUE). This figure was then multiplied by 24 to compute a daily CPUE (eggs/m^2/day). Average daily CPUE values were computed for each sampling station from the date the first herring egg was collected to the last egg collection date.

On the Santee River, blueback herring larvae were sampled with a plankton net (0.526-mm mesh, 0.5-m diameter) pushed for 5 min at a constant speed just below the water surface (Meador and Bulak 1987). Sampling was conducted during daylight hours (0900-1700 hours) from late February to mid-May before (1981-84) and after (1988-89) rediversion (Meador et al. 1984; West et al. 1988; Kempton 1990). A minimum of three tows were taken at each site every two days during the sampling season. Four of the five sampling sites (three main river channel sites and one tributary site:Wee Tee Lake), were at the same locations before and after rediversion. The fifth sampling site was a combination of two locations: the Santee River near (< 1 km) the projected entrance of the Rediversion Canal before the completion of rediversion and inside the mouth of the Rediversion Canal after rediversion (Figure 4). These two locations were analyzed as the same main river channel site. Wee Tee Lake and the main river channel site near Highway 17-A (Figure 4) were sampled for a total of six years (1981-84 and 1988-89) while the remaining sites were sampled for four years (1983-84 and 1988-89; Meador et al. 1984; West et al. 1988; Kempton 1990). The number of larval blueback herring in the net and volume of water filtered was used to calculate an estimate of relative abundance (larvae/100 m^3). Relative abundance estimates within a site did not vary significantly among tows

(Meador et al. 1984; West et al. 1988; Kempton 1990).) Tows within one site were then pooled to compute an average daily relative abundance for each site and sample date from the date the first blueback herring larvae were encountered to the last larval herring collection date in a sample year.

Data analysis

Information from the distribution data was used to calculate percent of the waterway length (main river channel and tributaries) used by blueback herring for migration or spawning. Percent of waterway use was calculated by estimating the total length of the tributaries and the main river channel and then estimating the length of the waterways that contained blueback herring. It was assumed that blueback herring used the nonsampled stretch of a tributary or main river channel between two adjacent sites as a migration route or for spawning. For calculations, herring were not assumed to be present beyond the last sampled upstream site that contained herring. A computerized image analysis system (Analytical Imaging Concepts, Irvine, CA) was used to estimate the distances on maps of the sample sites. These distances were then converted to km with the map scale. Ricefields were not included in the percent waterway length use calculation.

Average daily CPUE (eggs/m^2/day) for each station in Mulberry Ricefield and Cooper River (Osteen 1985; Thomas 1990) was statistically analyzed using a completely random split-plot design with the before and after rediversion periods as whole plots and the sites and sample years as subplots. Data were transformed [$\log_{10}(x + 0.05)$] because of the disproportionate number of stations without herring eggs. Analysis of variance (ANOVA) was used to detect differences in CPUE between sites (i.e., Mulberry Ricefield and littoral area of Cooper River), between periods (before and after rediversion) and among sample years (1981, 1982, 1988 and 1989). Individual means were compared with linear contrasts.

Average daily relative abundance of larval blueback herring (larvae/100 m^3) at five sites in the Santee River were examined with ANOVA on transformed data [$\log_{10}(x + 1.0)$]. The split-plot design used included sites and sample years as subplots, and periods as the whole plot. Meador (1982) and West (1984) provided the data for the before-rediversion period (1981-82 and 1983-84) and Kempton (1990) for the post-rediversion period data (1988-89). Linear contrasts were used to compare individual means, and a P value of 0.05 was considered significant for all analyses.

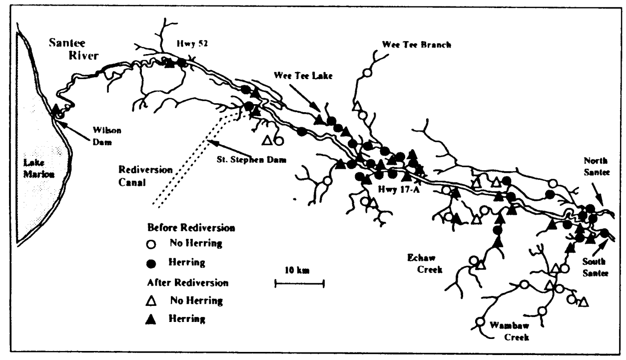

FIGURE 3.— Study section of the Santee River.

Results

Distribution

In the Cooper River, blueback herring (adults, eggs or larvae) were found at 17 of the 40 sites (42.5%) before rediversion compared to 26 of the 36 sites (72.7%) after rediversion. All main river channel sites and ricefields sampled in the Cooper River contained herring (Figure 2). However, only 5 of 28 tributary sites contained herring before rediversion compared to 12 of 22 tributary sites after rediversion.

The total calculated length of the surveyed waterways in the Cooper River was 101 km before and 64 km after rediversion. Calculated percentage of waterway length with herring adults, eggs or larvae was 29.5% before rediversion and 76.1% after rediversion. In Wadboo Creek, a main tributary, herring were found in 2.6% of the 62.3 km of surveyed stream length before rediversion and 52.4% of the 22.7 km stream length after rediversion. Herring

TABLE 1.— Analysis of the effects of rediversion period (before and after), sample site (Mulberry Ricefield and Cooper River) and sample year within period (1981 and 1982 before rediversion, and 1988 and 1989 after rediversion) on CPUE of blueback herring eggs (eggs/m^2/day).

Source	df	SS	MS	F	P
Period	1	32.95	32.95	61.44	<0.0001
Year within period (error A)	2	1.07	0.54		
Site	1	2.91	2.91	4.95	0.028
Period x site	1	1.94	1.94	3.29	0.717
Site x year within period	2	4.45	2.23	3.78	0.025
Error B	137	80.67	0.59		

TABLE 2.— Analysis of the effects of rediversion period (before and after), sample site (Highway 52, Rediversion Canal, Wee Tee Lake, Highway 17-A and Pheonix-McConnell boat landing), and sample year within period (1981, 1982, 1983 and 1984 before rediversion, and 1988 and 1989 after rediversion) on relative abundance of blueback herring larvae (larvae/100 m^3).

Source	df	SS	MS	F	P
Period	1	0.05	0.05	0.01	0.918
Year within period (error A)	4	16.50	4.13		
Site	4	2.67	0.67	2.70	0.030
Site x year within period	14	14.86	1.06	4.30	<0.001
Error B	412	101.75	0.25		

were also found farther in Wappoola Swamp after rediversion (Figure 2).

Blueback herring were collected at 26 of the 42 Santee River sites before rediversion and 23 of the 33 sites after rediversion. Herring were found at all the main river channel sites including the Rediversion Canal. Of the 32 tributary sites sampled before rediversion, herring occurred in 16 sites compared to 18 of 27 tributary sites after rediversion.

Approximately 303 km of the Santee River was surveyed before rediversion and 281 km after rediversion. The percent of the surveyed waterway lengths where herring were encountered was 62.6% before and 67.6% after rediversion. Blueback herring appeared to migrate similar distances upstream before and after rediversion. For example, herring were found 14.7 km upstream in Wee Tee Lake and 2.9 km up Wambaw Creek both before and after rediversion. The percent length of waterway used by herring before and after rediversion was the same in Wee Tee Lake (100%) and similar in Wambaw Creek (6.1% vs. 10.7%).

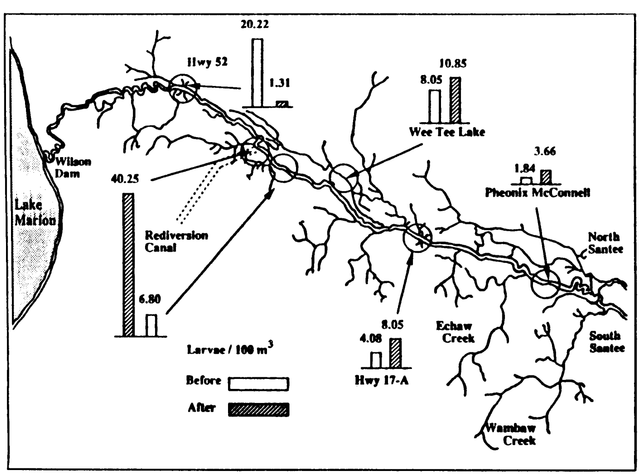

FIGURE 4.— Relative abundance of blueback herring in the Santee River before and after rediversion.

Relative abundance

The ANOVA of blueback herring egg CPUE data from Mulberry Ricefield and Cooper River before and after rediversion is summarized in Table 1. The overall mean (± SE) CPUE before rediversion (17.17 ± 6.31 eggs/m^2/day) and after rediversion (0.06 ± 0.04 eggs/m^2/day) was significantly different (P <0.001, Table 1). Analysis also revealed a significant difference (P = 0.025) with the sample site X year within period interaction, and linear contrasts separated three significantly different groups of interaction means. The CPUE for Mulberry Ricefield in 1982 (44.70 ± 17.63 eggs/m^2/day) which was the highest mean constituted one group. A second group of not statistically different means consisted of CPUE values before rediversion for Mulberry Ricefield in 1981 (4.41 ± 2.52 eggs/m^2/day) and for Cooper River in 1981 (1.21 ± 0.65 eggs/m^2/day) and in 1982 (2.59 ± 2.24 eggs/m^2/day). The mean CPUE values which made up the third group were from the after-rediversion period and included Mulberry Ricefield in 1988 (0.11 ± 0.11 eggs/m^2/day) and 1989 (0.05 ± 0.03 eggs/m^2/day), and Cooper River in 1988 (<0.01 eggs/m^2/day) and 1989 (0.01 ± 0.01 eggs/m^2/day). In each of these groups of means, the Mulberry Ricefield mean CPUE values were higher than the means for Cooper River. The overall mean value for Mulberry Ricefield (11.94 ± 4.57 eggs/m^2/day) was also significantly different from the Cooper River mean (0.95 ± 0.59 eggs/m^2/day).

Mean relative abundance of blueback herring larvae was similar (P = 0.918) before and after rediversion (Table 2). The effect of sample site location on the relative larval herring abundance was significant (Table 2). Mean relative abundance of herring larvae in the Rediversion Canal (29.26 ± 11.35 larvae/100 m^3) and Wee Tee Lake (9.24 ± 2.60 larvae/100 m^3) was significantly greater than the mean value for Highway 52 (7.95 ± 3.50 larvae/100 m^3), Highway 17-A (5.91 ± 1.29 larvae/100 m^3) and

Pheonix-McConnell boat landing (3.09 ± 0.74 larvae/100 m^3). Figure 4 summarizes the mean relative abundances of blueback herring larvae by sampling site and period. Before rediversion, those sites nearest Wilson Dam had higher relative abundances than the downstream sites whereas after rediversion the highest relative abundances were found in the Rediversion Canal near St. Stephens Dam. Significant year-to-year variation was observed in the relative abundance of larval herring. Higher mean relative abundance occurred in 1988 (18.87 ± 6.29 larvae/100 m^3), 1984 (12.81 ± 3.41 larvae/100 m^3) and 1981 (10.41 ± 2.64 larvae/100 m^3); an intermediate group of values occurred in 1989 (5.39 ± 2.58 larvae/100 m^3) and 1982 (2.95 ± 0.62 larvae/100 m^3); and the lowest value occurred in 1983 (0.05 ± 0.03 larvae/100 m^3). The sample site X year within period interaction was also significant ($P < 0.001$).

Discussion

Distribution

Loesch and Lund (1977) noted that blueback herring of the Connecticut and Thames rivers were very selective in choosing spawning sites. Spawning blueback herring selected areas with swift flows and hard substrate. In areas where blueback herring are sympatric with alewife *A. pseudoharengus*, blueback herring selected lotic spawning sites over lentic sites (Loesch 1987). In the southern portion of its range, blueback herring chose old ricefields, cypress swamps, and oxbows over nearby streams for spawning (Christie et al. 1981; Meador et al. 1984; Loesch 1987). Our study indicates that blueback herring in the Santee-Cooper System used both the lentic, soft-bottom habitat of Mulberry Ricefield and the lotic, high-flow habitat of the Rediversion Canal for spawning.

Loesch (1987) also suggested that blueback herring will adapt their spawning site selection behavior in the face of changing environmental conditions. The discharge regime of Pinopolis Dam changed from high consistent discharges before rediversion to low, less consistent discharges after rediversion (Osteen et al. 1989; Thomas et al. 1992). Mulberry Ricefield, an important spawning site for blueback herring before rediversion (Osteen et al. 1989), was less accessible to migrating blueback herring after rediversion (Slack 1991). Reduced access to ricefields may have forced herring to seek other spawning sites. Herring were found farther upstream in the tributaries of the Cooper River after rediversion. Upstream distribution of spawning blueback herring is limited both by habitat suitability and access (Loesch and Lund 1977).

Although discharge increased in the Santee River with rediversion, the pre- and post-rediversion distribution of blueback herring in the Santee River was similar. Flood releases from Wilson Dam during the spawning season were the most important hydrological events influencing blueback herring spawning habitat in the Santee River (West et al. 1988). After rediversion, flood releases occurred only once from 1986 through 1989 compared to four times in a 5-year period (1978, 1981-84) before rediversion (Christie et al. 1981; Meador et al. 1984; West et al. 1988; Kempton 1990; Thomason 1991). Our ability to detect changes in herring distribution with rediversion may be limited by the yearly differences in flood releases.

Relative abundance

The post-rediversion estimate of relative egg abundance (CPUE) in Mulberry Ricefield and littoral area of Cooper River represents a 99.6% diminution from the pre-rediversion relative abundance estimate. Adult herring are attracted by high flows (Collins 1952). The reduced discharges associated with rediversion probably attracted fewer blueback herring to the Cooper River. Cooke and Eversole (1994) observed a 77-80% decline in the annual averages of fish passage at Pinopolis Dam and the commercial herring landings in the Cooper River between 5-year periods before rediversion (1980-84) and after rediversion (1986-90). Reduced adult herring numbers explain only a part of the 99.6% decline in egg CPUE, while the remainder may be a function of access and suitability of the sampled habitats for spawning blueback herring. For example, Slack (1991) observed that access to ricefields (via dike breaches) was limited during periods of low discharge and ebb tide after rediversion. Thomas et al. (1992) also noted that after rediversion, herring eggs were captured only from deep water stations in Mulberry Ricefield and that shallower water areas of the ricefield were exposed during periods of low discharge.

According to the results of a tag-recapture study, the estimated number of adult blueback herring in the Santee River increased from an average of 3.1 million herring/year from 1980 to 1984 to 6.6 million/year from 1986 to 1990 (Cooke 1990). Although larval herring relative abundance increased at four of the five sampling sites in the Santee River after rediversion (Figure 4), none of these relative abundance estimates were significantly higher than pre-rediversion estimates. Significant variation in relative abundance was observed with sample year regardless of the rediversion period. Past Santee River studies indicate hat larval herring relative abundance reflects the iming and duration of flood releases (Meador et al. 1984; West et al. 1988; Kempton 1990). The year-to-year variation in the flood release patterns in the Santee River is probably one reason why the differences in relative abundance between pre- and post-rediversion periods were not detectable.

The section of Santee River near Highway 52 (and upstream of the confluence of the Rediversion Canal) was an important spawning site before rediversion (West et al. 1988). After rediversion, the highest observed relative abundance of larval herring was in the Rediversion Canal. Gill net data from sites near the mouth of the Rediversion Canal indicated that, after rediversion, most of the migrating adult herring were moving into the canal rather than up the Santee River toward Wilson Dam (Christie and Cooke 1987). Loesch (1987) reported that blueback herring will disperse to new areas and increase in abundance under the appropriate hydrological conditions. Our data indicate that adult blueback herring abandoned historic spawning sites near Highway 52 in favor of new sites in the Rediversion Canal. However, it is not clear whether the addition of 8 km of spawning habitat in the Rediversion Canal will compensate for loss of approximately 60 km of riverine habitat above the canal.

Summary

The U.S. Army Corps of Engineers (1975) predicted that the fishery resources in the Cooper River would decline with rediversion and the resultant reduction of discharge from Pinopolis Dam. Relative abundance estimates of blueback herring eggs (CPUE) indicate this was the case in Mulberry Ricefield and the littoral area of the adjacent Cooper River. Surprisingly, the number and length of tributaries used by blueback herring increased after rediversion. We hypothesize that in the absence of suitable habitat in ricefields, blueback herring were forced to seek sites in the more lotic habitats of the Cooper River.

Population estimates (tag-recapture data) indicate an increase in the herring population in the Santee River after rediversion (Cooke 1990) as predicted by the U.S. Army Corps of Engineers (1975). Blueback herring used 8 km of the Rediversion Canal as a spawning site whereas the use of 60 km of the historic spawning habitat in the Santee River upstream of the canal confluence was diminished with rediversion. Mean relative larval herring abundance estimates for the Santee River were similar before and after rediversion. Flood releases from Wilson Dam influenced blueback herring spawning behavior (Meador et al. 1984; West et al. 1988) and probably limited our ability to detect statistical differences between pre- and post-rediversion periods.

Since the Rediversion Canal has developed into an important blueback herring spawning site, it is critical that the facility at St. Stephen Dam be operated in a manner that will allow not only for successful spawning but also fish passage (Cooke and Eversole 1994). Careful management of the discharge regimes in both rivers during the spawning season is one of the more promising ways to lessen the impacts of rediversion on the blueback herring resource. Arrival at a discharge regime acceptable to both resource and public works managers will require compromise by all parties.

Acknowledgments

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American Shad Fisheries of North Carolina with Emphasis on the Albemarle Sound Area

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Abstract.—American shad *Alosa sapidissima* have supported an extensive fishery in North Carolina and other Atlantic coast states since the colonial period. The North Carolina Division of Marine Fisheries has monitored American shad throughout the major coastal systems, with continuous monitoring in the Albemarle Sound area since 1972. Gill nets, pound nets, and haul seines have historically been the principal commercial fishing gear, with gill nets accounting for the majority of the landings. The areas fished and gear employed in the shad fishery have remained essentially unchanged since the late 1800's. However, in some areas the amount of certain types of gear has decreased, while increases have been noted in other areas. The amount of harvest has declined significantly since the late 1800's. North Carolina's American shad harvest has increased from that in the 1970's, and although stable, remains at a reduced level.

American shad *Alosa sapidissima* have historically supported a major fishery in North Carolina, as well as in other Atlantic coast states. The native Americans and European colonists, who settled along the extensive sounds and rivers, found shad to be a valuable food source. Shad which ascended the streams in large numbers during the spring were caught, salted, and smoked, and were an important seasonal food.

American shad are distributed along the Atlantic coast from the St. Lawrence River, Canada, to the St. Johns River, FL and are most abundant from Connecticut to North Carolina (Walburg and Nichols 1967). Shad ascend all coastal rivers in North Carolina and are most abundant in the Cape Fear, Neuse, Tar-Pamlico, Roanoke, and Chowan rivers (and their tributaries) and Albemarle and Pamlico sounds (Figure 1). The fishery throughout the

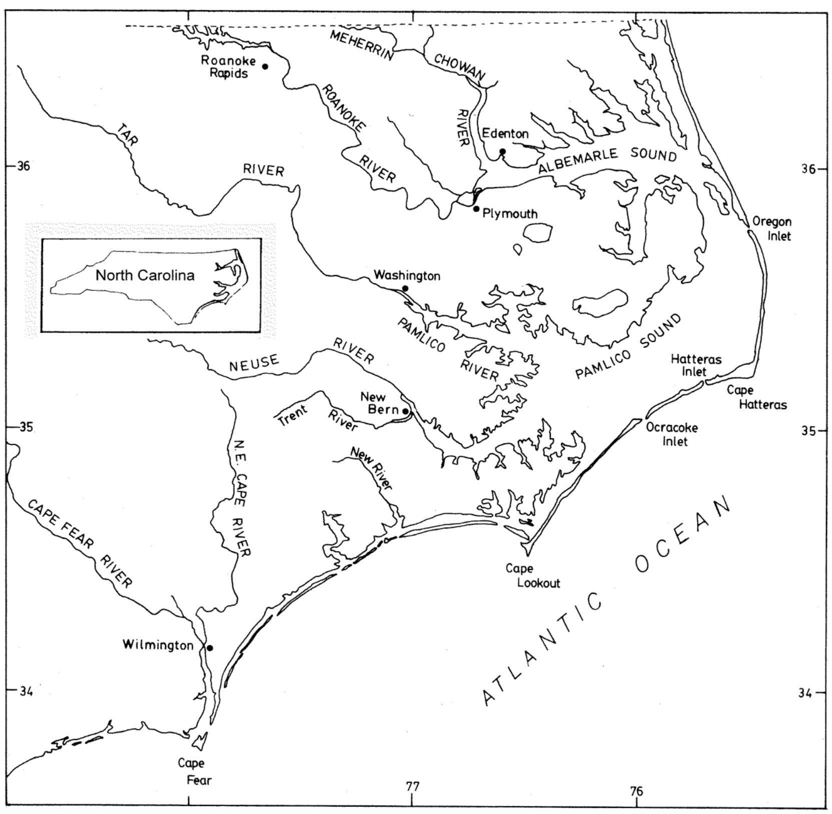

FIGURE 1.—Map of Albemarle and Pamlico sounds showing the major tributaries.

TABLE 1.— American shad landings and value in North Carolina,1880-1992 (from Chestnut and Davis 1975 and N.C. Division of Marine Fisheries, Morehead City).

Year	Landings (1000 kg)	Recorded Value ($1000)	Value in 1987 dollars ($1000)	Year	Landings (1000 kg)	Recorded Value ($1000)	Value in1987 dollars ($1000)
1880	1,462	330	4853	1959	190	105	410
1887	2,171	298	4806	1960	157	127	488
1888	2,599	295	4683	1961	305	168	639
1889	2,452	280	4444	1962	347	191	713
1890	2,640	306	5016	1963	314	168	618
1896	4,015	417	7316	1964	290	127	458
1897	4,069	363	6482	1965	485	214	754
1902	2,981	385	6417	1966	318	170	578
1904	1,466	313	5048	1967	352	155	512
1908	1,781	373	5652	1968	382	128	403
1918	752	377	3366	1969	326	137	411
1923	1,076	583	4740	1970	432	193	550
1927	1,083	475	3831	1971	308	117	316
1928	1,415	573	4659	1972	212	112	289
1929	868	350	2846	1973	145	85	206
1930	532	210	1765	1974	167	106	236
1931	400	139	1275	1975	109	83	169
1932	420	126	1299	1976	75	65	124
1934	578	193	1874	1977	54	55	98
1936	497	177	1670	1978	182	145	240
1937	317	106	964	1979	126	122	186
1938	468	165	1528	1980	90	88	123
1939	389	137	1280	1981	159	190	241
1940	364	120	1101	1982	187	183	218
1945	414	199	1508	1983	202	187	214
1950	499	340	1692	1984	265	241	265
1951	564	300	1422	1985	149	152	161
1952	671	377	1762	1986	169	229	236
1953	539	293	1344	1987	148	215	215
1954	656	258	1167	1988	128	171	165
1955	294	160	702	1989	146	214	197
1956	350	193	818	1990	142	170	150
1957	379	209	857	1991	125	201	171
1958	223	123	494	1992	107	194	160

coastal area has employed drift gill nets, stake gill nets, anchored gill nets, pound nets, haul seines, bow nets, fish wheels, and hook and line.

Since the late 1800's, North Carolina has consistently ranked in the top three states for commercial landings of American shad along the east coast (Walburg and Nichols 1967). The peak reported landings in North Carolina occurred in 1897 at over 4 million kilograms, but in recent decades the landings have declined sharply (Sholar 1977; Johnson 1982). An increase in landings was noted from 1981 to 1987, but was less than landings of the 1960's (Table 1). Since the late 1880's, landings along the entire Atlantic coast of the United States have shown a continued decline (ASMFC 1985). Since the late 1800's, overfishing, construction of dams, and pollution have been blamed for the decline in landings (Cheney 1896; Blackford 1916; Roelofs 1951; Talbot 1954; Chittenden 1969; Klauda et al. 1976; Boreman 1981).

Shad are pursued extensively in the spring, both commercially and recreationally. In recent years, the commercial importance of shad has decreased in some areas, while the species supports an increasingly important recreational fishery in others. Annual North Carolina landings in 1992 were 107,598 kilograms. This annual poundage has decreased from that reported by Johnson (1982: 186,594 kg), but has increased from that which Sholar (1977) reported (54,934 kg; Table 1).

History of the Shad Fishery

In 1896, the American shad harvest from the Albemarle Sound was among the most important on the Atlantic coast. Stevenson (1899) reported a harvest of 2,162,998 kg in 1896 for the Albemarle Sound area, but the harvest had decreased to 52,401 kg in 1904 (Cobb 1906) for the same area, a decline of 97.6%. Historically, Virginia usually ranked first and North Carolina second (Walburg and Nichols 1967), but by 1960, the landings for North Carolina only ranked third along the east coast. Landings and values reported for the state by Chestnut and Davis (1975) have fluctuated widely over the years, but show a continued decline since the late 1800's (Table 1). During 1972-1992, North Carolina landings averaged 147,584 kg, with a range of 54,934 to 265,590 kg (Figure 2).

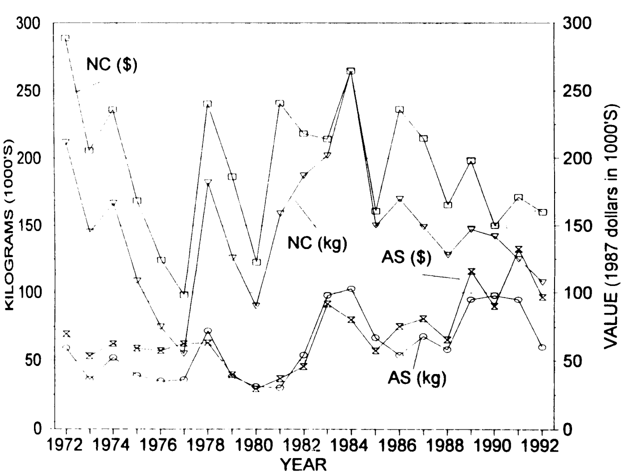

FIGURE 2.—Landings and value (1987 dollars) of North Carolina American shad from 1972 to 1992. NC = North Carolina; AS - Albemarle Sound.

The North Carolina shad fishery can be divided into the commercial fishery and the recreational (inland) fishery. Although some of the gear used is employed by both fisheries, they are treated separately because the fisheries are administered by two separate agencies. The commercial fishery is under the jurisdiction of the North Carolina Division of Marine Fisheries, whereas the inland section is under the North Carolina Wildlife Resources Commission. The jurisdictional areas are described in North Carolina Fisheries Regulations for Coastal Waters, 1992-1993 (NCDEHNR 1992).

There are four principal commercial fishing methods used in North Carolina to capture shad: anchored gill nets, staked gill nets, pound nets, and haul seines. In the Albemarle Sound area these gear are essentially the same as those of the late 1800's (Smith 1907), although the length of the gear has changed. In 1896, gill nets averaged 18.3 m long and were set in strings of 50 to 500 nets with 133-140 mm stretched-mesh (Walburg and Nichols 1967). Gill nets now average 9 to 73 m in length, and mesh sizes range from 102-140 mm stretched-mesh.

Pound nets during the late 1800's were set along the shores of the sounds and rivers with 1 to 25 pounds or hearts in each string. Since the 1960's, the majority of the pound nets has been set in the rivers, and the leads seldom exceed 183 m in length. The haul seines that were used to catch shad in 1896 averaged 2275 m long, were 3.7-4.9 m deep, and had a stretched-mesh size of 51 mm in the bunt and 76 mm in the wings. The haul seines of the 1950's and 1960's in the Albemarle Sound area averaged 137 m long (Walburg and Nichols 1967). Only a remnant haul seine fishery currently exists in the Albemarle area and does not target shad.

Gill nets have historically contributed the highest percentage of the landings, since they are fished for the larger roe (female) shad (Stevenson 1899; Walburg and Nichols 1967). Several other types of commercial gear were used: bow nets, fyke nets, drift gill nets, and fish wheels. These methods have contributed very little to the total harvest in the Albemarle area. Most of the harvest, past and present, is handled through dealers in Elizabeth City, Columbia, Manns Harbor, Wanchese, Colerain, and Chowan County, and then shipped to northern markets.

The inland fishery gear is composed of bow nets, anchored and drift gill nets, and hook and line. A bow net resembles a large landing net with an oval opening up to 3 m in width and 3.7 m in length. Bow nets were usually fished from the bank or from a boat. Drift gill nets are approximately 18-36 m in length and are fished in coastal rivers by drifting downstream with the current. Some hook and line effort for shad occurs in the upper Roanoke, Chowan (Nottoway and Blackwater rivers) and Meherrin rivers. Baker (1968) estimated a shad harvest of approximately 3,900 American shad from these areas in 1966 to 1967, but the shad catches that result from this gear cannot be quantified. The catch from bow net and hook and line will not be considered.

Since 1896, the areas fished and gear used in the shad fishery have remained essentially unchanged. In some areas the amount of certain types of gear has decreased, whereas increases have been noted in other areas. The extent of the fisheries harvest has declined and the fishery could not continue if totally dependent on shad.

Commercial Harvest Survey

American shad landings and values for North Carolina and the Albemarle Sound have fluctuated considerably during the past 21 years (Figure 2). The decline in North Carolina landings has been more dramatic than that in Virginia or South Carolina, but has not resulted in stocks reaching the low levels observed in Maryland (ASMFC 1985).

For the 1972 to 1992 period, the lowest North Carolina landings (54,943 kg) were recorded in 1977. Total North Carolina American shad landings increased during 1983 and 1984 (Figure 2) but declined in 1985 to 1987.

Gill nets, pound nets, and haul seines have historically been the principal commercial fishing gear in North Carolina for American shad (Walburg and Nichols 1967). Gill nets (anchored and drift) have contributed the highest percentage of American shad to the North Carolina landings for 20 of the past 21 years (Figure 3). Only in 1977 did pound net catches dominate the state's landings.For this time period: 67.9% were taken by anchored gill nets; 18.5% by pound nets; 10.5% by drift gill nets; 2.9% by haul seines; 0.1% by trawls; and <0.01% by other gear.

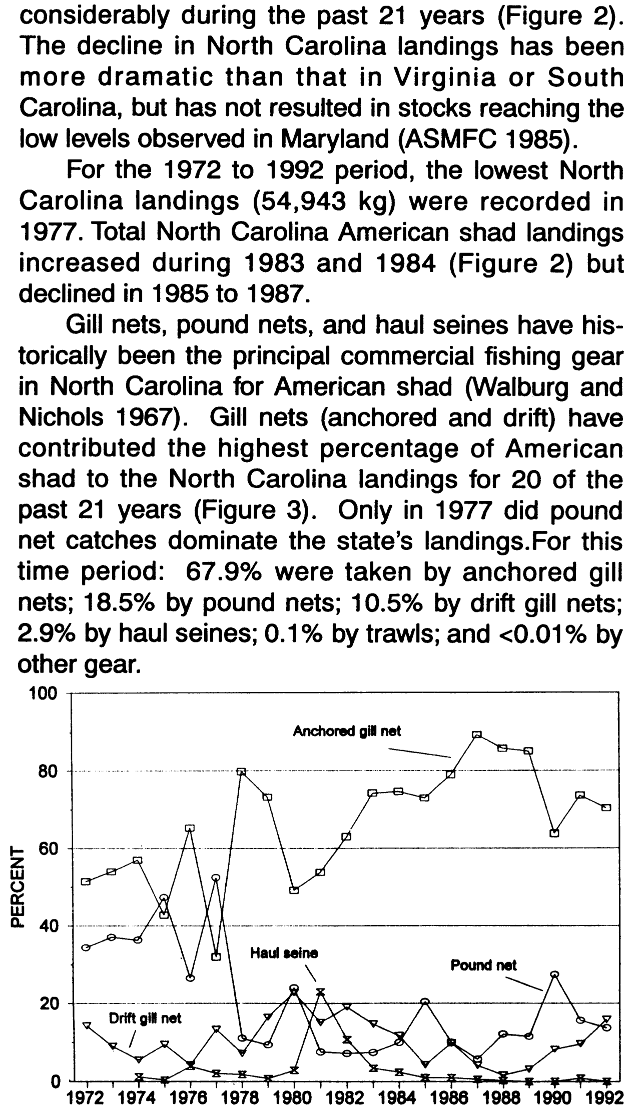

FIGURE 3.—Percentage of North Carolina American shad landings by gear for 1972 to 1992.

Albemarle Sound Area

Albemarle Sound, located in the northeastern portion of North Carolina, is a shallow estuary extending 88 km in an east-west direction (Figure 1), and averages 11 km wide and 5-6 m deep. Ten rivers drain into Albemarle Sound, which joins Pamlico Sound through Croatan and Roanoke sounds, and in turn, empties into the Atlantic Ocean via Oregon Inlet. Currituck Sound joins the Albemarle from the northeast. Most of the tributaries to the sound originate in extensive coastal swamps, but the headwaters of the Roanoke River are located in the Appalachian foothills of Virginia. The Roanoke and Chowan rivers are the principal tributaries, and areas of these rivers are known to function as American shad spawning areas (Street et al. 1975; Johnson et al. 1981; Winslow et al. 1983, 1985).

The Roanoke River is a relatively narrow stream which follows a winding course to its mouth below Plymouth, where it enters western Albemarle Sound. A dam was constructed in 1955 on the river at Roanoke Rapids (river km 254), North Carolina (Carnes 1965), preventing further upstream movement. However, American shad have not been reported above the Scotland Neck bridge (river km 193) for many years (Baker 1968).

The Chowan River, formed by the junction of the Blackwater and Nottoway rivers near the North Carolina-Virginia border, flows 88 km to northwestern Albemarle Sound. The Meherrin River is one of the major tributaries of the Chowan River and originates in the piedmont area of Virginia. The Meherrin River follows a southeasterly course after entering North Carolina and meets the Chowan River 66 km above the mouth. American shad spawning has been documented in the Meherrin and Chowan rivers. The North Carolina portions of the Chowan and Meherrin rivers are free of obstructions that may restrict adult shad during their spawning run. A more detailed description of Albemarle Sound and its tributaries is given by Street et al. (1975) and Winslow et al. (1983, 1985).

The shad fisheries of the Albemarle Sound area became important about 1869, with the greatest development occurring in the next 25 years (Walburg and Nichols 1967). Until 1860, haul seines were the only gear used and for some years continued to be the principal gear. Pound nets were first used in the Albemarle area in 1870 (Cobb 1906). Their popularity grew until 1896, then declined because of cost of the gear and its operations, as well as a decline in harvest (Walburg and Nichols 1967). In the late 1800's and early 1900's, the commercial harvest season normally ran from early February to mid-April. The legal fishing season in 1960 was 1 January to 1 May in coastal waters, and 1 January to 1 June in inland waters. During this time it was illegal to set gill nets in

Albemarle Sound west of the NC Highway 32 bridge, and in the Chowan River, from the river mouth upstream to Holiday Island. By 1960, nets were set primarily for striped bass *Morone saxatilis* and river herring *Alosa* spp., with shad catches being incidental, due to the continued decline in shad landings (Walburg and Nichols 1967). The present fishing season is about the same as it was in 1960, although there is no regulated shad season. Management actions taken in the springs of 1989 to 1992 for striped bass conservation probably acted as conservation measures for American shad as well. Certain areas in Albemarle Sound were closed to gill netting and mesh size restrictions were enacted during this time.

The Roanoke River fishery changed considerably from 1896 to 1960, as shad landings decreased and the amount of gear fished decreased (Walburg and Nichols 1967). In 1896, shad fisheries in the Roanoke River were limited to the lower river, from Williamston to the river mouth. By 1960, the fishery extended farther up the river, to the Scotland Neck bridge. Shad catches were incidental for all gear which were directed at striped bass and river herring. Regulations adopted by the North Carolina Marine Fisheries Commission in 1980 eliminated set gill nets in the Roanoke River from April through May and restricted the mesh size of drift gill nets to no greater than 76 mm stretched-mesh. In 1981, the North Carolina Wildlife Resources Commission eliminated bow netting on the Roanoke River. These regulations were passed to protect striped bass during their spawning run, but also protected shad in their migration up the river to spawn.

The Chowan River differed from other areas in 1896 because pound nets and seines were the primary gear used to capture shad, accounting for 98% of the catch. By the mid-1900's, pound nets and seines were fished primarily for river herring and gill nets for shad. As with all other areas, landings decreased drastically from 1896 to 1960 (Walburg and Nichols 1967).

The Albemarle Sound area has accounted for the highest percentage of the North Carolina American shad landings in 17 of the 21 years between 1972 and 1992. In 1977, the Albemarle Sound area contributed the highest percentage (65.8%) of the state's total landings although the total state landings were the lowest in this period (Figure 4a). The lowest total reported in the Albemarle area occurred in 1981 (30,296 kg; Figure 2), but the state total was above the 16 year average from 1972 to 1987 (153,003 kg).

Winslow et al. (1983) reported the lowest river herring landings on record in 1981 for the Albemarle Sound area. The North Carolina Division of Environmental Management has collected data for several years on river flow and the concentration of pulp mill effluent discharged into the Chowan River in Virginia, just north of the North Carolina-Virginia border. During years with normal river flow (e.g. 1979-1980), the pulp mill effluent is not detectable in the river prior to spawning runs. However, in the low flow of 1981 the effluent was detected in the river (Winslow et al. 1983). Everett (1983) concluded that in the spring of 1981, the high concentration of pulp mill effluent in the river interfered with the normal river herring migratory pattern. This may also have affected American shad movement which may have resulted in decreased landings.

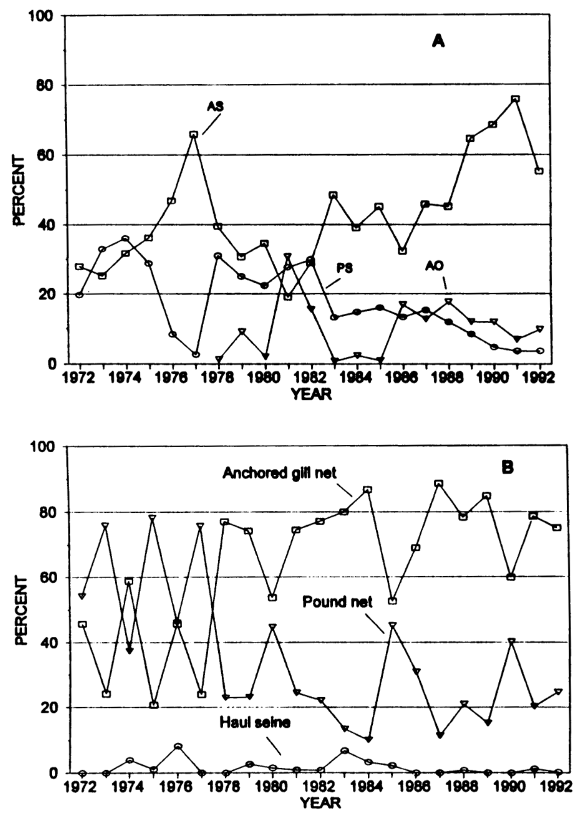

FIGURE 4.—Percentage of the total North Carolina American shad landings (A) by major water body (AS = Albemarle Sound; PS = Pamlico Sound; and AO = Atlantic Ocean); and (B) percentage of American shad landings by year and gear for Albemarle Sound, 1972 to 1992.

The principal commercial fishing gear in the Albemarle Sound area has historically been the same as those for the entire state (Walburg and Nichols 1967). The percentage of landings by year and gear for 1972 to 1992 from the Albemarle Sound area are shown in Figure 4b. Gill nets were the dominant gear for 16 of the 21 years and pound nets were the dominant gear for the other five. The landings for the Albemarle area for these 21 years show that gill nets have accounted for 67.8%, pound nets for 30.5%, haul seines for 1.6% and other gear for < 0.01% of the harvest (Figure 4b).

Pamlico Sound

Pamlico Sound lies in a northeast-southwest direction. It is 113 km long and ranges from 16 to 48 km wide (Figure 1). To the south it joins Core Sound and to the north it connects with Albemarle Sound through Roanoke and Croatan sounds. Two large rivers, the Neuse and the Tar-Pamlico, enter the sound from the west, and the Inland Waterway connects Pamlico and Albemarle sounds in the northeast portion. The waters of Pamlico Sound enter the ocean through Oregon, Hatteras and Ocracoke inlets. Fish migrate from the ocean to the tributaries of Pamlico and Albemarle sounds through these inlets (Walburg and Nichols 1967).

In 1973, 1974, 1981 and 1982, Pamlico Sound contributed a higher percentage to the total North Carolina American shad landings than did the Albemarle Sound area (Figure 4a).

Cape Fear River and Tributaries

The Cape Fear River is formed by the confluence of the Haw and Deep rivers in the North Carolina piedmont. From there it flows southeast for 322 km and empties into the ocean 40 km below Wilmington (Figure 1). The principal tributaries in the coastal plain are the Black and Northeast Cape Fear rivers, and both are important shad streams.

In 1896, shad could ascend 291 km up the Cape Fear River but, at present, it is free of obstructions only from the mouth to Lock and Dam No. 1, 48 km upstream of Wilmington. Except during periods of extended high flow, the Lock and Dam blocks fish passage to the river above. A fishway was constructed in the dam in 1925 but it was ineffective for shad, thus the primary spawning area is immediately below the Lock and Dam. Two other dams have been constructed above Lock and Dam No. 1 since that time. Neither the Northeast Cape Fear River nor the Black River has obstructions to fish passage. The major spawning areas are approximately 48 km above Wilmington on the Black River, and approximately 56 km upstream on the Northeast Cape Fear River (Walburg and Nichols 1967).

The percentage of shad landings (1972 to 1992) contributed by the Cape Fear River to the total state harvest has fluctuated from a high of 22.8% in 1980 to a low of 1.9% in 1988 (Figure 5).

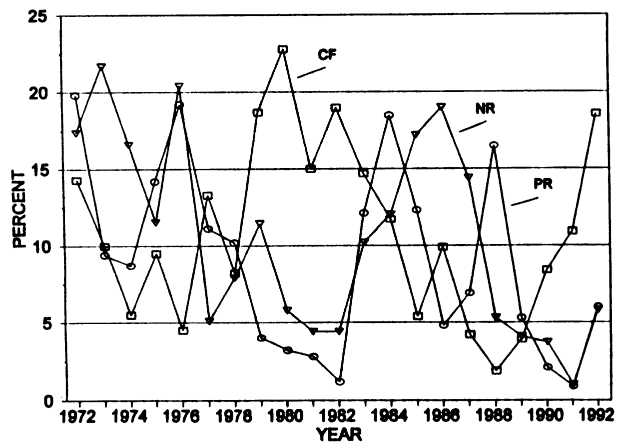

FIGURE 5.—Percentage of the North Carolina American shad landings by selected river systems: CF = Cape Fear River; NR = Neuse River; and PR = Pamlico River.

A steady increase in harvest has been observed since 1989.

Neuse River and Tributaries

The Neuse River is formed by the confluence of the Eno and Flat rivers. It flows southeast 290 km before entering the southern part of Pamlico Sound (Figure 1). The principal tributaries are the Trent and Little rivers and Contentnea Creek.

American shad formerly ascended the Neuse River in great numbers as far upstream as Raleigh, 483 km from the coast. Most of the catch, however, was made within 35 km below and above New Bern (Walburg and Nichols 1967). This stretch of river remains the predominate harvest area today. The spawning grounds in the Neuse River extended from New Bern to Goldsboro, 177 km upstream, where the low-head Quaker Neck Dam (equipped with a pool-type fishway), was constructed in 1952. During periods of high flow, fish moving upstream can swim over the dam and reach the tributaries, but in low flow, fish must use the fishway. The Coastal America Project, a federally assisted program, has identified Quaker Neck Dam as one to be removed. The removal of this dam will provide better access to the historical spawning areas. The Trent River is free of obstructions and shad can ascend 40 km upstream from the mouth of the tributary. A lowhead dam exists on Little River and is also proposed to be removed as part of the Coastal America Project. In Contentnea Creek, Wiggins Mill Dam, 48 km from the mouth, prevents upstream movement of fish.

Walburg and Nichols (1967) stated that in 1896, the Neuse River was the most important shad stream between the St. Johns River, Florida, and the James River, Virginia. Hawkins (1980) reported that American shad landings for 1972 to 1979 from the Neuse River accounted for only 14.5% of the total North Carolina shad catch (Figure 5). The Albemarle Sound contributed an average of 64% of the state total during the same period. These percentages may be misleading, because fish from outside these areas are sometimes sold to area fish dealers and shad from Albemarle Sound are also sold to dealers in other areas. Even so, these landings are the best estimate of commercial catch available.

Tar-Pamlico River

The Tar-Pamlico River begins as the Tar River which flows 290 km southeast from Granville County to Washington where it becomes the Pamlico River. The Pamlico River flows 60 km and empties into Pamlico Sound (Figure 1). Prior to the 1900's, the shad fishery extended from Pamlico Sound upstream to a natural falls at Rocky Mount. In the mid 1900's, a dam was constructed below Rocky Mount which blocked upstream passage (Walburg and Nichols 1967). American shad landings in the Pamlico River have fluctuated during the period 1972 to 1992, ranging from 1% to 20% of the total state landings.

Atlantic Ocean

During the late 1970's, an ocean fishery for American shad developed along the Outer Banks and in the southern portion of the state. The major gear were beach haul seines and gill nets. The beach haul seine accounted for the majority of the landings during 1978, 1981, 1982, and 1984. The landings from gill nets dominated the other years: 1979, 1980, 1983, and 1985 to 1992. From 1978 to 1985, the areas north of Cape Hatteras accounted for the majority of the state's ocean shad landings. In 1986, an ocean gill net fishery for shad developed in the southern portion of the state off the Cape Fear River. In 1981, the Atlantic Ocean contributed 30.6% to the state's total landings (Figure 4a). Up to 96.6% of the total Atlantic Ocean landings have been taken from the southern area since 1986.

Factors Affecting Decline in Abundance

The American shad run in the Albemarle Sound area, as well as the rest of eastern North Carolina, has been greatly reduced from its magnitude during the late 19th century (ASMFC 1985). North Carolina landings have fallen precipitously from a peak of over 4 million kg in 1897 to a low of 54,943 kg in 1977. However, shad landings data are considered to be inaccurate due to the decrease in the number of true commercial shad fishermen in recent years. An unknown (possibly large) quantity of shad are caught in North Carolina by recreational fishermen using commercial gear. These fish are kept for personal consumption or are sold to friends or small, seasonal markets. In any case, these shad never enter the official statistics. The lack of catch-effort data for the fishery also prohibits a true picture of the shad resource. Even with these inadequacies, the trend is the same; fewer fish are being caught each year. Currently there are insufficient data to determine the actual cause or causes for the decline.

Taylor (1951) found that shad showed signs of "depletion" or biological scarcity in North Carolina. He stated that "shad [are] probably at a permanent biological disadvantage and may never be as abundant or migrate as in former years." The decline of shad in North Carolina has been attributed to pollution (industrial, pesticides, siltation), dams, and overfishing. These factors have been suggested for the entire Atlantic coast (Roelofs 1951; Mansueti and Kolb 1953; Walburg and Nichols 1967). While these factors may have contributed to historical declines in landings, their role in the last 20 years has not been clearly delineated. Roelofs (1951) considered siltation and dams to be the major factors in the decline of shad in North Carolina, but no first-line dams have been constructed on any North Carolina river since 1955.

In recent decades the Albemarle Sound and its tributaries have experienced deterioration of water quality which has been considered to have affected the *Alosa* stocks. However, the effect is not as clearly defined as in the Delaware River (ASMFC 1985). Several factors resulting from poor water quality may be involved in preventing a recovery: (1) blue green algae blooms may smother larvae or produce toxins; (2) low dissolved oxygen levels may result from algal blooms; (3) food chain interruption due to changes in the algal forage base may be eliminating preferred food items; and (4) migration patterns of spawning adults may be altered during low flow years when high concentrations of pulp mill effluent is present in the lower tributaries to western Albemarle Sound. These factors have not been rigorously explored.

Pollution of nearly all estuarine waters along the east coast has certainly increased over the last 20 years due to all aspects of development within the watersheds. The general degradation of water quality is a coast-wide problem. The construction of better sewage plants during the past 20 years has reduced raw sewage discharge which would benefit water quality conditions, however, it would not result in a reduction of other types of pollutant discharges (ASMFC 1985). Boreman (1981) reported that dams and pollution are two stresses that have been blamed for stock reduction, however, more subtle stresses may have gone undetected.

Talbot (1956) statistically determined that excessive fishing pressure was the major factor affecting shad runs in the Hudson River. Nesbit (1939) stated "the decline in shad production in Maryland, Virginia, and North Carolina is the result of overfishing" but Roelofs (1951) concluded that overfishing was very unlikely in North Carolina and, at that time, unproven. Goodyear (1977) suggested that the observed decline in landings may have been caused by increased exploitation, but were more likely caused by the reduced ability of stocks to withstand additional stress, i.e. reduction in the stock's "compensatory reserve."

Currently no proof exists to explain the drastic reduction of shad in North Carolina. The combined effects of many factors could be acting on the population to account for the decline. Undoubtedly, pollution and migration barriers have taken their toll, but excessive harvest, although unproven, probably has had a role. When the effects of each of these factors are combined with high post-spawning mortality, the overall result is a seriously depleted shad resource. Mansueti and Kolb (1953) suggested the existence of some type of natural biological cycle within the population, but no evidence has been presented to substantiate their view.

Conclusions

The North Carolina shad resources, despite slight increased landings during the last eleven years, continue to be depressed. Changes have occurred in the spawning and nursery habitats as a result of the encroachment of man, from reduction in some areas to complete elimination in others. River and sound environments have been altered physically as well as chemically.

The data collected in North Carolina on American shad have been beneficial in many aspects. Data have been utilized in the analysis of proposed joint ventures with foreign fishing interests. The available information on American shad in North Carolina has proven useful in the development of an east coast shad and river herring plan coordinated by the Atlantic States Marine Fisheries Commission. The detection of areas utilized by American shad as spawning and nursery areas has proven beneficial in the regulation of development in those areas.

Despite the benefits, current anadromous fishery data in Albemarle Sound do not yield sufficient information to evaluate the reason for the stock decline. One of the major deficiencies is a lack of catch-effort data. Once catch-effort statistics have been obtained for several years, studies can proceed to determine population sizes and factors responsible for the fluctuations in abundance, and appropriate management measures can be developed. In addition, information on harvest and utilization is desperately needed; without it the shad population can never be adequately evaluated. The Atlantic States Marine Fisheries Commission's shad and river herring plan is beginning to address these data needs.

Action needs to be taken to reduce or eliminate pollution of the waters and habitat destruction. With adequate biological data, reliable harvest data, and productive habitat, there is no reason why the American shad population in the Albemarle Sound area, as well as throughout eastern North Carolina, cannot again support valuable fisheries.

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American Shad Restoration in the Susquehanna River

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Abstract.—Prior to development of dams, American shad *Alosa sapidissima* utilized hundreds of kilometers of the Susquehanna River in Pennsylvania and supported an extensive fishery. Between 1904 and 1932, four hydroelectric dams were built in the lower 88 km of river and available spawning habitat was reduced by 99%. For the past 32 years, federal and state fishery resource agencies have worked cooperatively with private utility companies to restore American shad and other migratory fishes to the Susquehanna River. Spawning habitat suitability and fish passage feasibility studies were completed during the 1960's. Cooperative agreements among the parties were reached in 1970, 1982, 1985, and 1988 which led to development of fish trapping and passage facilities at Conowingo Dam, stocking of adult shad into spawning waters above all dams, construction and operation of a shad hatchery, and studies related to monitoring downstream passage of juvenile shad, turbine survival, and stock assessment. The nine member Susquehanna River Anadromous Fish Restoration Committee oversees all restoration activities, developing annual work plans and tracking expenditures amounting to over $400,000 each year. Utility companies have additionally spent several hundred thousand dollars each year for trap and transfer of adult shad, and turbine survival and passage studies at their projects. During the past eight years, shad numbers returning to Conowingo Dam have increased 25-fold, with the population estimate in the tailrace increasing from 3,500 to 86,000 fish. Catch of shad in fish lifts at Conowingo increased from a few hundred in 1983-1984 to over 25,000 in 1991 and 1992. The shad hatchery in Pennsylvania has stocked over 100 million fry and fingerlings during this period. Based on analysis of otoliths of the returning shad in recent years, it appeared that over 70% were of hatchery origin. Philadelphia Electric Company completed a $12 million fish passage facility at Conowingo Dam in 1991. Licensees for the three upstream hydroelectric projects have recently reached an agreement with intervener resource agencies to complete final design, hydraulic testing and construction of permanent upstream passage facilities at their dams by the end of this decade. Ultimate goals of this program are to develop self-sustaining runs of 2 million shad and 5 million river herring above all dams in the Susquehanna River.

The Susquehanna River once supported large and valuable runs of the anadromous American shad *Alosa sapidissima* and river herrings *A. aestivalis* and *A. pseudoharengus*. Construction of canal dams, water pollution and overfishing reduced stocks and the development of four hydroelectric dams in the lower 88 km of river since 1910 excluded these fishes from 97% of their historic range. For the past 30 years, fishery resource agencies have worked with the power companies that are licensed to operate the dams in an effort to rebuild shad stocks to the point where multimillion dollar fish passage construction could be justified. The program to restore shad to the Susquehanna is one of the largest of its kind ever undertaken.

The River and the Dams

The Susquehanna is the largest river basin on the Atlantic Coast of the United States draining 71,225 square kilometers from Cooperstown, New York, to Havre de Grace, Maryland (Figure 1). The Susquehanna provides over 50% of the freshwater input to the Chesapeake Bay. The river is wide, steep, shallow and rock-strewn. For these reasons the Susquehanna was never a major commercial waterway like other large eastern rivers.

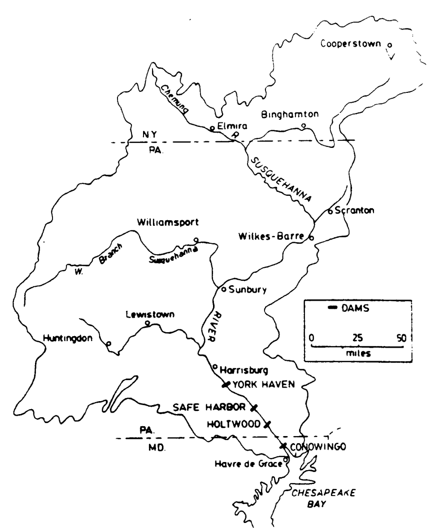

FIGURE 1.—Map of the Susquehanna River Basin.

Much of the 715 km length of the main stem and many kilometers of major tributaries once served as spawning and nursery habitat for migrating American shad, river herring, and American eel *Anguilla rostrata*. Prior to the development of canal dams in the 1830's, dozens of commercial seine fisheries operated in the north branch from Sunbury, Pennsylvania, to the New York state line. After canal dams were built, migrations were limited to the lower 72 km of river ending at Columbia, Pennsylvania.

The canal system was abandoned in the 1880's as railroads took over freight and passenger transport. Early efforts to place fishways at the dam at Columbia were largely unsuccessful, but occasional breaches caused by ice damage did allow shad and herring to move upstream and modest fisheries redeveloped between 1888 and 1910. During this same period, major fisheries for shad and herring were pursued near the river mouth and on the Susquehanna Flats using improved gill nets, pound nets and seines.

With the advent of the electric era, the Susquehanna was viewed as ideal for placement of hydroelectric dams. The first dam was built at York Haven at river kilometer (rkm) 88 in 1904. This 2-5 m high structure did not stop spring migration during high flow. However, when the 17 m Holtwood Dam was completed in 1910 (rkm 40), it served as the upstream limit of migration. Fish passages were built at Holtwood but both the powerhouse ladder and west bank sluiceway failed to pass shad. Fishways were abandoned and the Holtwood owners agreed to make annual payments to the Pennsylvania Fish Commission in lieu of fish passage.

In 1928, the Conowingo project was completed just 16 km upstream from the river mouth in Maryland. This 29 m high structure was one of the largest hydroelectric dams in the country. The state-of-the-art was such that fish ladders were not required at Conowingo, and shad and herring runs were further limited to only the river below that dam. The fourth and last hydroelectric dam was built at Safe Harbor (rkm 51) in 1932. The Safe Harbor Dam is 23 m high and, as was the case with Holtwood and Conowingo, licensees have made annual payments to the affected states in lieu of fish passage.

The combined generating capacity for the four Susquehanna River projects is 1050 MW through 53 turbines. These range in size from 1 MW Francis turbines to 65 MW Kaplan turbines. Powerhouse discharge capacities range from 453 m^3/s at York Haven with very limited peaking capability to 3,116 m^3/s at Safe Harbor with 85 million cubic meters of usable storage in a 3,000 hectare impoundment.

Early Years of Shad Restoration

Considerable progress was made in development of working fish passages at high dams on the West Coast, particularly on the Columbia River, during the late 1930's and 1940's. Numerous federal laws were enacted to develop a better partnership with the states for fishery management, restoration and research. These included the Anadromous Fish Conservation Act, the Federal Aid in Sport Fish Restoration Act, Fish and Wildlife Act of 1956, and the Fish and Wildlife Coordination Act. This renewed interest in fishery restoration and improved state-of-the-art in fish passage prompted Pennsylvania, Maryland, New York, and the federal government to initiate efforts to restore shad to the Susquehanna River.

In 1960, the Pennsylvania Fish Commission (PFC) contracted with West Coast experts to evaluate the feasibility of constructing workable fish passage facilities at Susquehanna dams. The "Susquehanna Fishway Study" (Bell and Holmes 1962) indicated that fish passage could be built at all four projects but that before such a costly program began, it was recommended that an important first step would be to evaluate the suitability of the river above the dams for shad spawning.

The U. S. Fish Commissioner assigned representatives from the Bureau of Sport Fisheries and Wildlife (now U. S. Fish and Wildlife Service) and the Bureau of Commercial Fisheries (now National Marine Fisheries Service) to work with the three basin states to study the question of suitability. During 1963-1967 such a study was performed and it was determined that over 555 kilometers of the main stem from Columbia, Pennsylvania, to Binghamton, New York, and portions of the lower West Branch and Juniata rivers were suitable for all life stages of American shad (Carlson 1968).

The results of these early studies led to the formation of the Susquehanna Shad Advisory Committee (SSAC) in 1969. This group consisted of policy and technical committees, each with voting representatives from Pennsylvania, New York, Maryland, and the U. S. Fish and Wildlife Service (USFWS). The SSAC worked closely with dam licensees and in 1970 reached an agreement to initiate a program to restore shad to the Susquehanna River. That agreement provided for construction of an experimental fish lift at Conowingo Dam to collect shad for transport upstream to spawn and to assess the number and kinds of fishes approaching the dam. The agreement also committed upstream licensees to fund an effort to collect and stock up to 50 million fertilized shad eggs each year into suitable waters above all dams.

The fish lift at Conowingo was built and began operating in 1972. Unfortunately, the shad stock in the Upper Chesapeake Bay was declining rapidly and Tropical Storm Agnes brought record flooding to the river with extensive siltation of the Susquehanna Flats spawning area. During the period 1972-1981, only 1,273 shad were collected at the trap. Maryland closed its fisheries for shad in 1980 as commercial catch fell to an all time record low (Figure 2).

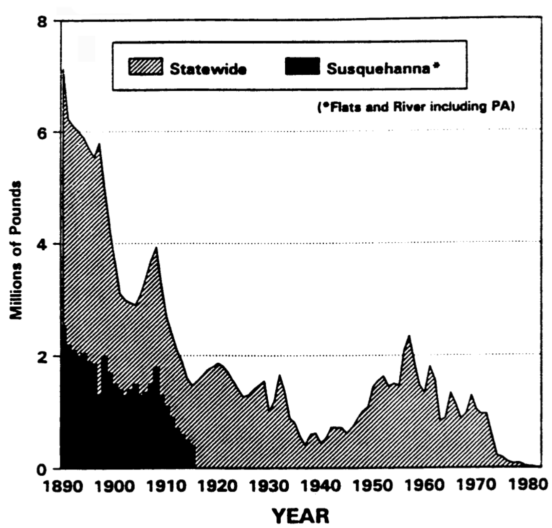

FIGURE 2.—Maryland commercial shad landings from 1890 to 1981 and landings from the Susquehanna Flats and the Pennsylvania portion of the Susquehanna River from 1890 to 1915.

Many East Coast rivers and the Columbia River in Oregon were sampled for shad eggs. During 1971-1976, over 216 million eggs were delivered to the Susquehanna and stocked at numerous locations in the main stem and major tributaries. However, apparent lack of success in producing outmigrating juveniles led to the development of an intensive shad culture hatchery in 1976.

The 1970 agreement expired in 1975 and licensees agreed to continue to fund the restoration program on a year-to-year basis thereafter. The SSAC was reorganized in 1976 and renamed Susquehanna River Anadromous Fish Restoration Committee (SRAFRC). Voting representation was provided to the Philadelphia Electric Company (PECO), the upstream licensees (one vote for three utilities) and the National Marine Fisheries Service.

Using utility funding, the Pennsylvania Fish Commission (now PA Fish and Boat Commission) built and began operating the Van Dyke shad hatchery on the Juniata River near Thompsontown, Pennsylvania. Since 1977, all shad eggs collected for the program have been delivered to Van Dyke. The purpose for this facility is to culture shad fry to 18 days of age for stocking nursery waters above the dams in the Susquehanna. Limited fingerling production occurred at pond sites in Pennsylvania and Maryland. During 1976-1981, a total of 27 million viable shad eggs was delivered to Van Dyke and 10 million fry and fingerlings were produced and stocked.

Hydroproject Relicensing, Hearings and Settlement

In August 1980, the Federal Energy Regulatory Commission (FERC) issued new long-term operating licenses to the four Susquehanna River hydroelectric projects. The issue of shad restoration was set aside for hearings. FERC hearings were conducted between October, 1981, and February, 1982, at Washington, D. C. Interveners, including the U. S. Department of the Interior (represented by USFWS), PFC, Susquehanna River Basin Commission (SRBC), and Maryland Department of Natural Resources (DNR) argued that the licensees should be required to construct fish passage facilities and take other measures to assure that restoration could succeed. Utilities agreed that a demonstration program of stock rebuilding should continue, but argued against immediate construction of fish passage as being premature considering the lack of shad below Conowingo Dam.

Meanwhile, upstream licensees (Pennsylvania Power and Light Co., Safe Harbor Water Power Corp., and York Haven Power Co.) reached a settlement agreement with the PFC and the SRBC in 1981 relating to a proposed expansion project at Safe Harbor and committed to spend up to $750,000 over a five year period to continue the restoration effort already underway. PECO financed trap operations and transfer of shad above Conowingo during these years of discussion pending a FERC decision. Also, the USFWS established a restoration program coordinator position in Harrisburg, Pennsylvania, in response to requests from the basin states.

Settlement negotiations related to the FERC hearing continued for several years and in December 1984, the three upstream licensees reached agreement with all interveners to continue the demonstration program for an additional 10 years. This agreement provided $3.7 million for the period 1985-1994 for egg collection, hatchery operations, out-of-basin transfer of adult shad, juvenile evaluation, downstream monitoring studies, and other efforts approved by SRAFRC. The agreement also required licensees to meet with interveners and initiate design of permanent fish passage facilities at Holtwood, Safe Harbor and York Haven projects once PECO agreed to build such facilities at Conowingo. Upstream licensees further agreed to take over costs associated with trucking fish from Conowingo to spawning waters above all dams once permanent facilities came on-line at Conowingo. At this time, SRAFRC was expanded to include voting representation from each of the power companies involved and the SRBC.

Separate settlement discussions were held with PECO during 1980-1988. Meanwhile, in 1986, FERC ruled that PECO should build an interim fish lift at the east end of the powerhouse at Conowingo and to operate this and the west bank lift until at least three years beyond the termination of the upstream agreement (i.e. 1997). All parties were allowed an opportunity to petition FERC during this period for either construction of permanent passage facilities or a termination of the program depending on their convictions that the program was or was not likely to succeed.

Recent Restoration Successes

Because of the lack of adult shad returning to Conowingo Dam, SRAFRC began collecting gravid fish from the Connecticut and Hudson rivers and transferring them to spawning waters in the Susquehanna. Between 1981-1987, over 30,000 shad (mostly Hudson) were stocked between Beach Haven (rkm 269) and Oakland, Pennsylvania (rkm 571). This was discontinued after 1987 because of the lack of apparent reproduction from these fishes (few juveniles were collected), and because the more desireable lower Susquehanna River stock was showing excellent signs of expansion.

Shad catch at the Conowingo west fish lift improved dramatically during 1982-1988 with annual collections increasing from a few hundred to many thousands. Also, the DNR-sponsored tag and recapture population estimate in the lower river and Upper Bay improved five-fold from 8,000 shad in 1984 to almost 40,000 in 1988.

The success being shown in the program led to a new settlement with PECO in late 1988. That agreement resolved all outstanding issues in the FERC relicensing process, providing for continuous minimum flows, dissolved oxygen compliance in the Conowingo discharge, and construction of a $12 million permanent fish passage facility rather than the FERC-ordered interim device. The new fish lift at the east end of the Conowingo powerhouse, capable of handling 750,000 shad and 5 million herring, was built in 1990 and began operation on April 1, 1991. With permanent passage construction at Conowingo, and in accordance with terms of their 1984 agreement, licensees of the Holtwood, Safe Harbor, and York Haven projects completed preliminary designs and cost estimates for fish passage at their dams in 1991.

With two trapping facilities operating at Conowingo, shad collections increased to over 25,000 per year in 1991-1992 (Figure 3). Since 1982, a total of about 75,000 adult shad have been successfully transferred to spawning waters above the dams. As might be expected, the DNR population estimate in the upper Bay continued to increase, reaching a high of 140,000 shad in 1991.

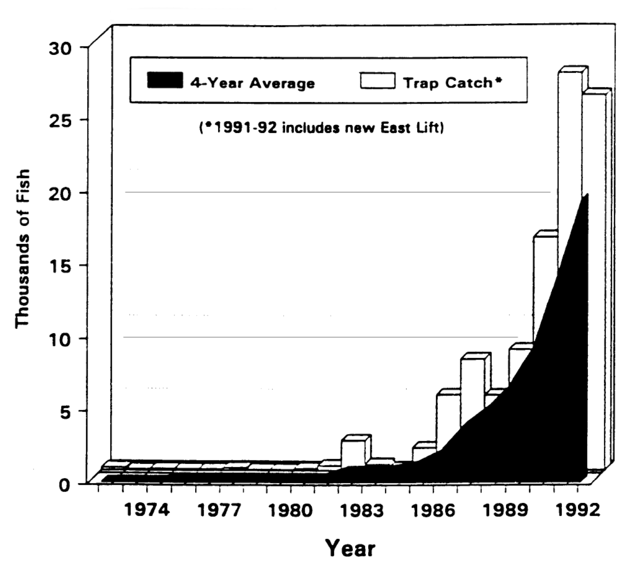

FIGURE 3.—Summary of American shad catch from the Conowingo Dam fish lifts, 1972 to 1992.

The PFC hatchery effort improved each year and between 1982 and 1992, over 107 million shad fry and fingerlings were produced and stocked (Figure 4). In 1985-86, PFC researchers developed a mass-marking technique for larval shad using short-term immersions in 200 ppm tetracycline (TC) antibiotic solution and TC-laced feeds (Hendricks et al. 1991). Multiple marks were imparted on otoliths allowing identification of hatchery versus wild fish, individual egg source strains, stocking locations, and fry versus fingerling plants. Marked year-classes first appeared in Conowingo collections in 1989 and since then, it has been determined that 67% to 76% of the return stock of adult shad each year is of hatchery origin.

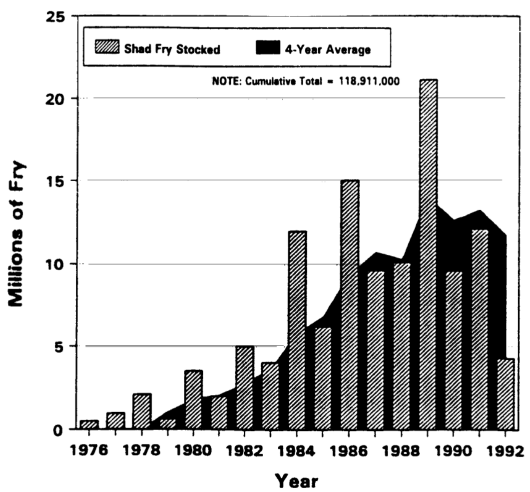

FIGURE 4.—Number of American shad fry stocked into the Susquehanna River, 1976 to 1992.

Throughout the program effort, SRAFRC has spent considerable resources to monitor and enhance downstream migration of juvenile shad. Shad are collected each autumn using seines, sluice and lift nets, from power plant cooling water strainers and screens, by electrofishing and other means. Shad collected in these studies are returned to PFC researchers for analysis of hatchery marks on otoliths. Underwater acoustics have been used to study movements and migration timing and to estimate relative abundance of juvenile shad at select sites. Behavior modifying devices such as strobe and mercury lights and sound generators were tested to attract shad to safe passage routes and repel them away from the turbines.

Radio telemetry studies have been conducted with juvenile shad to describe movement and migration patterns in impoundments and near dams, and turbine survival during passage. Radio telemetry has also been used extensively with adult shad in the Susquehanna program to document movements in dam tailwaters, migrations in impoundments and the river following transport from Conowingo or from out-of-basin sources, turbine and spill survival at dams, and concentrations of fish to identify spawning locations. Results of all work performed in the Susquehanna River shad program since 1982 are documented in annual reports to the restoration committee (SRAFRC 1982-1992).

Future Outlook

Approximately $1.5 million is currently spent each year on the Susquehanna shad restoration effort. Most of this is paid by the utilities in accordance with terms of their settlement agreements with resource agencies. Recent negotiations with upstream utilities culminated in an agreement in principle in October, 1992, to complete final design, hydraulic model testing, and to construct permanent fish passage facilities at Holtwood and Safe Harbor no later than spring 1997, and at York Haven by spring 2000. Preliminary cost estimates for these first phase facilities range from $17 million to $30 million.

Continued growth in the shad stock returning to Conowingo and successful operation of fish passage facilities at all dams by the end of this century should provide increased natural production in the river. Upstream utilities will continue to fund hatchery production and stocking of shad fry and fingerlings until all passage facilities are operational.

Considerable work remains to maximize survival of downstream migrant adult and juvenile shad at hydroelectric projects. Operational modifications, controlled spills or specially designed by-pass facilities may be required at some sites. As the return population continues to grow, fish passage facilities may have to be enlarged to keep pace with the run. Annual population targets for the completed restoration program are 2 million shad and 5 million river herring above all dams in the Susquehanna.

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Effects of Stocking and Natural Reproduction on Recovery of American Shad in the Upper Chesapeake Bay

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Abstract.—We assessed the effects of two management actions on the population of American shad *Alosa sapidissima* which spawns in the upper Chesapeake Bay: stocking of larvae and juveniles and a moratorium on the capture of spawning adults in the Maryland waters of the Chesapeake Bay and tributaries. Estimates of year-class strength of American shad, measured as number of spawning recruits, from 1977 through 1984, have increased at an exponential rate. The number of fish stocked explained a highly significant amount of variation in strength of the 1977-1984 year-classes. The estimated size of female spawning stock did not show a significant relation to year-class strength. We calculated expected returns to the upper Chesapeake Bay from the number of fry stocked, using estimates of turbine-caused mortality rates from four hydroelectric stations on the lower Susquehanna River and using estimated age-specific larval, juvenile, and preadult mortality rates from the Connecticut River. Expected returns from stocking were 0.00086 of numbers stocked, averaging 5.6 ± 2.21% (mean ± 1 SE) of the estimated 1977 to 1985 year-classes. In contrast, otolith studies of adult American shad from the fish lifts at the Conowingo Dam indicated 70% were hatchery-reared. The discrepancy could be due to bias in the mortality estimates or to the possibility that the fish lifts collect a non-random sample of the upper Bay population, being biased towards stocked fish. The contribution of hatchery-reared fish to growth of the upper Bay population may be intermediate between these estimates.

In 1980, the Department of Natural Resources of the State of Maryland declared a moratorium on capture of American shad in the state's portion of the Chesapeake Bay due to drastic stock decline. Concurrently, an interstate effort was undertaken to restore American shad spawning runs in the upper Susquehanna River under the guidance of the Susquehanna River Anadromous Fish Restoration Committee (SRAFRC). Four large hydroelectric facilities, constructed on the lower river between 1904 and 1932 (SRAFRC 1983), have blocked migration to the historic spawning grounds. Fish passage facilities are planned as part of this restoration effort. SRAFRC has funded the Van Dyke Hatchery, operated by the Pennsylvania Fish and Boat Commission (PFBC). Since 1977, fry have been stocked annually in the Juniata River, a major tributary entering the Susquehanna above Harrisburg, Pennsylvania. Since 1986, fry have also been stocked several miles below the Conowingo Dam in a joint operation between the Maryland Fisheries Division and the PFBC. Fry stocked in the Juniata must pass the four major hydroelectric stations on the lower River: York Haven, Safe Harbor, Holtwood, and Conowingo dams.

Since 1980, the upper Bay spawning stock has increased exponentially (Markham and Weinrich 1994). Both stocking and the moratorium may have contributed to this increase. In order to assess the effects of these management actions, we explored the question: What effect has stocking had on the population increase of American shad spawning in the upper Chesapeake Bay?

We explored the relation between recruitment and stocking by examining: 1) total recruitment to the spawning run; 2) the ratio of recruitment to stock; 3) the relation between recruitment and both the number of fry stocked and spawning stock size; 4) estimates of expected recruitment from the stocking effort; and 5) comparisons between our estimates of the number of wild and hatchery fish and the estimates obtained by otolith analysis.

Study Site

The study site is the upper Chesapeake Bay, including the mouths of the Northeast, Elk, and Bohemia rivers and the Susquehanna Flats including the lower 10 miles of the Susquehanna River to the Conowingo Dam (Figure 1). The Susquehanna

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is the largest river on the East coast of the US and is the main tributary of the Bay, contributing 60% to 70% of the Bay's freshwater volume. Tidal influence ends about five miles up the Susquehanna. Shad historically spawned in the lower river and Flats.

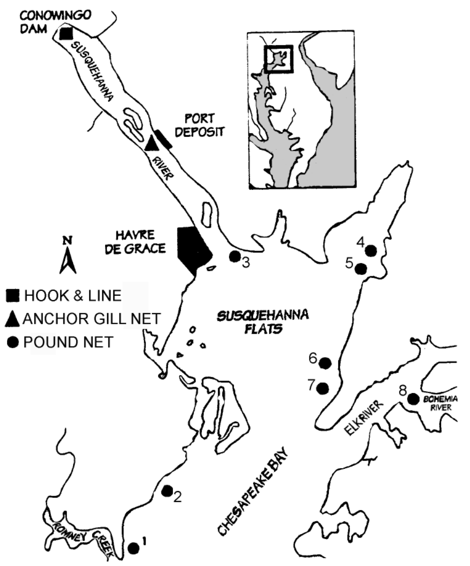

Figure 1.—Location of sampling sites used in data collection. Distance from the mouth of the Susquehanna River to Conowingo Dam is ten miles. Anchored gill net data were excluded from analysis for this study due to bias. Names of pound nets are: 1-Romney Creek; 2-Cherry Tree Point; 3-Perry Point; 4- and 5-Cara Cove; 6-Rocky Point; 7-Beaver Dam; and 8-Bohemia River.

Methods

We calculated estimates of total recruitment to the spring spawning run for the 1977-1984 year-classes (year-class strength) using our estimates of age structure and our Petersen population estimates to evaluate recruitment levels for indication of augmentation by stocking. Due to variable maturation, recruitment of American shad has been categorized as the platoon type (Ricker 1975; Crecco and Savoy 1987a). Estimates of year-class strength were calculated from estimates of stock size, age composition, and the proportion of repeat spawners of the spawning run of American shad in the upper Chesapeake Bay and the Conowingo tailrace from 1980 through 1991 (Markham and Weinrich 1994). Proportions of virgin shad from each year-class were multiplied by Petersen estimates of spawning stock size for each year. These products were then summed over years to estimate year-class strength (Ricker 1975). The latest year-class to fully recruit to the spawning run in 1991 was the 1984 year-class. The earliest year-class for which we have complete estimates is the 1977 year-class since stock assessment started in 1980 and age 3 was the youngest age present in the sample. To fit an exponential equation to the time series of year-class strength, we linearized the exponential equation $N_t = N_0e^{rt}$ (Poole 1974) by taking natural logarithms of both sides of the equation and then performed a linear regression on the log-transformed data to obtain an estimate of r (Younger 1985; Sokal and Rohlf 1981).

We calculated ratios of recruitment to parental female spawning stock size (recruitment-stock ratios) for each year-class from 1980 through 1991 by dividing our estimate of year-class strength by the estimated female spawning stock size for each year. For comparison, we also calculated recruitment-stock ratios for the Connecticut River, which has a healthy population of American shad, using data in Crecco and Savoy (1987b).

We used simple linear regression analysis to determine whether numbers of fry stocked and size of spawning stock were related to subsequent recruitment. We obtained estimates of numbers of fry and juveniles stocked from annual SRAFRC reports and regressed year-class strength on the number stocked. To investigate the stock-recruitment relation, we regressed year-class strength on female spawning stock size. Residuals were examined for evidence of violation of the standard assumptions of regression analysis (Sokal and Rohlf 1981). If such violations were detected for a given model, that model was rejected.

We calculated estimates of expected recruitment to the spawning runs from the number of larvae and juveniles stocked between 1977 and 1991, using age-specific estimates of larval and juvenile mortality from the Connecticut River (Crecco et al. 1983; Savoy and Crecco 1988). These estimates included estimated turbine mortality from the four hydroelectric plants on the lower Susquehanna River. Estimates of mortality (developed with balloon tags) were 0.02 at Safe Harbor Dam (A_{SF}; Heisey et al. 1992), 0.25 at Holtwood Dam (A_H), and 0.05 to 0.20 at Conowingo Dam (A_C; P. Heisey, personal communication). Estimates for Conowingo were tentative and varied depending on which turbines were in use; we have used 0.20 for these calculations. No data were available for York Haven Dam (A_{YH}) but since its turbines were similar to those at Holtwood, we have used the Holtwood value.

Total turbine effects were calculated as

$$S_{turbine} = (1\text{-}A_{YH})\ (1\text{-}A_{SF})\ (1\text{-}A_{H})\ (1\text{-}A_{C})$$

where $S_{turbine}$ is the survival rate after mortality from turbine passage through all four dams and A is mortality at each dam. Estimates of mortality from other sources were obtained from Crecco et al. 1983 (Table 1) for larvae and juveniles. Post-juvenile mortality from age 101 d to 5 years was estimated to be Z = 4.85 from Savoy and Crecco (1988). The average age of recruitment to the spawning run for upper Bay American shad from 1988 to 1992 was 4.54 years. Larvae were stocked at 18 d old and were 13.4 ± 0.176 mm (mean ± 1 SE). However, interpolation in Table 4 of Crecco et al. (1983) shows the average length of Connecticut River larvae at 18 d old to be 16.7 mm, which is 24% longer. Because we have no data on mortality rates of 18 d old, 13.4 mm larvae, we made the assumption that rates were equivalent to the larger Connecticut River larvae. Due to sampling problems, Crecco et al. (1983) gave no estimate of mortality for larvae from 23 mm to 42 mm, so we assumed that survival was equal to that for juveniles 42 mm to 80 mm. There is no mortality estimate for the period from 80 mm at a mean age of 78 d to the age of 100 d. We assumed that the daily mortality rate was the same as that for the period 101 d through 365 d, which was estimated to be M = 0.01 ± 0.002 d^{-1} by Savoy and Crecco (1988). Each of these three assumptions was conservative for mortality. Survival from other mortality sources was estimated by calculating survival from each age-length increment and taking the product of these S values.

Estimates of proportions of wild versus stocked shad have been calculated for 1989-1991 from otolith analyses of returning American shad caught in the fish traps at Conowingo Dam (Hendricks et al. 1991b; 1992a). Since 1986, stocked shad have had nearly 100% retention of oxytetracycline in their otoliths; this material is easily detected under ultraviolet radiation (Hendricks et al. 1991a). Adults from earlier stockings were detected by differences in otolith microstructure from wild fish (Hendricks et al. 1991b; 1992a). Hatchery larvae grow more slowly than wild larvae, producing smaller daily otolith increment widths. Results of blind trials of their method of distinguishing stocked from wild shad indicated a small error rate of identification (Hendricks et al. 1991b; 1992a), produced by overlap of the range of increment widths between wild and hatchery shad. We calculated a correction factor to account for errors of identification and then adjusted estimates of the proportion of stocked shad collected in the fish traps at Conowingo presented in Hendricks et al. (1991a; 1992b). Calculation of the estimated absolute number of returning adult hatchery-reared American shad to the Conowingo fish traps in 1989-1991 was made using catch-at-age data for the Conowingo fish traps from RMC (1990; 1991; 1992) and estimates of proportions of hatchery-reared and wild American shad by sex and age in Hendricks et al. (1991b; 1992a).

Results

Year-class strength from 1977 to 1984, as measured in recruitment of virgin spawners to the spring

TABLE 1.— Mortality rates by size and age increment for American shad in the Connecticut River from Crecco et al. (1983). Age increments and daily mortality rates are averages of rates for 1979-1982, given as the mean ± 1 S.E.

Size increment (mm)	Mean age increment	Mean duration (days)	Percent mean daily mortality rate
18 - 21	19.4 ± 0.55 d to 28.0 ± 0.56 d	8.6	9.1 ± 0.58
21 - 23	28.0 ± 0.56 d to 33.0 ± 1.15 d	5.0	5.8 ± 0.51
23 - 39	33.0 ± 1.15 d to 40 d	7	unknown
40 - 80	40 d to 80 d	40	1.88 ± 0.48

TABLE 2.— Estimates of number of female adult shad in the upper Chesapeake Bay spawning stock, total recruitment to the spawning stock (year-class strength) and number of fry stocked per year. (*) recruitment is incomplete for the 1985 year-class.

Year	Stock size (females)	Recruitment (thousands)	Number Stocked (millions)
1977	–	18	1.0
1978	–	31	2.1
1979	–	9	0.6
1980	2,800	8	3.5
1981	2,400	16	2.0
1982	6,400	24	5.1
1983	7,700	45	4.1
1984	2,800	81	12.0
1985	5,000	125*	6.3
1986	5,300		15.2
1987	9,300		9.7
1988	17,300		10.2
1989	25,800		21.2
1990	59,500		9.8
1991	71,000		12.3

spawning run to the upper Chesapeake Bay, has increased exponentially (Table 2) and was described by the equation

$$N_t = 3{,}997e^{0.484t}$$

(r^2 = 0.97, P 0.001), where N_t is year-class strength in thousands and t is time in years from 1978 (t = year - 1978).

Recruitment-stock ratios for the Susquehanna River prior to 1984 (0.9 - 2.9) are within the same range as those for the Connecticut River (0.6 - 3.9; Figure 2). During 1984, the ratio in the Susquehanna River increased to 15.2. Although recruitment from the 1985 and 1986 year-classes was incomplete as of 1991, their ratios, 11.6 and 5.5, would only increase as recruitment continued.

During 1977-1984, year class strength was highly correlated with the number of stocked fry (Figure 3). The regression equation with the best fit was:

$$\text{Year-class strength (thousands)} = 7.19 + 5.67 \text{ number stocked (millions)}$$

(R^2 = 76.7%, P = 0.004). Estimates of the number of females in the spawning stock were not correlated with resulting year-class strength for 1980-1985.

The survival rate after mortality from passage through all four hydroelectric stations, $S_{turbine}$, was 0.441; and in terms of mortality, $M_{turbine}$ = 0.82. Survival from stocking to 21 mm was estimated as S_1 = 0.424 and M_1 = 0.858; from 21 mm to 23 mm, S_2 = 0.742 and M_2 = 0.298; from 23 to 80 mm, S_3 = 0.425 and M_3 = 0.856. For the last two increments, we used age rather than length: from 78 d (the mean age of 80 mm larvae) to age 100 d, M_4 = 0.22 and S_4 = 0.803; from 101 d to 5 years, M_5 = 4.85; S_5 = 0.008. Total survival from stocking to recruitment into the spawning run at a mean age of 5 years

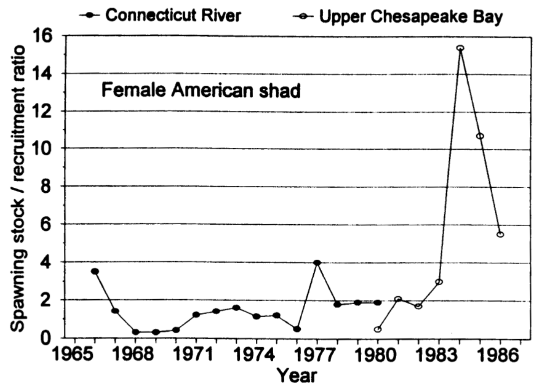

Figure 2.—Recruitment-stock ratio calculated as the total recruitment from a given year (year-class strength) divided by the estimate of female spawning stock size in the upper Chesapeake Bay in that year. Ratios from the Connecticut River were calculated from data in Crecco and Savoy (1987).

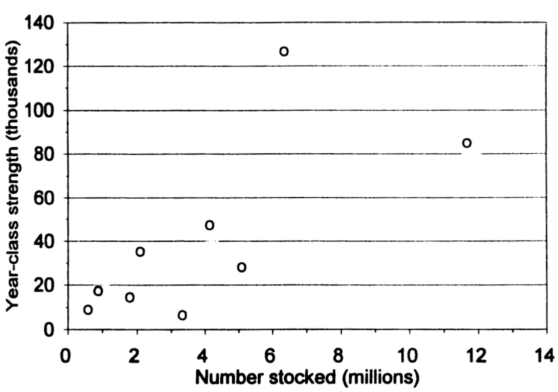

FIGURE 3.—Number of American shad fry (larvae plus fingerlings) stocked in the Susquehanna River by PFBC, 1977-1984, plotted against estimates of year-class strength. See text for regression statistics.

was:

$$S_{total} = 0.00086 = S_1 * S_2 * S_3 * S_4 * S_5$$

Total mortality was:

$$M_{total} = 7.082 = M_1 + M_2 + M_3 + M_4 + M_5$$

To include turbine effects on survival for larvae stocked above the four hydroelectric plants:

$$S_{t+T} = S_{total} * S_{Turbine}$$

and substituting from above produces 0.00038 = 0.00086 * 0.441. Turbine effects on total mortality were

$$M_{t+T} = M_{total} + M_{Turbine}$$

and substituting values produces 7.902 = 7.082 + 0.82.

In most years, fingerlings were 100 d old when stocked but in some years 70 d old fingerlings were stocked (Table 3). The 70 d old fish were assigned a mortality of 1.8%/d. Survival to day 100 was 0.982^{30} = 0.580. The estimated mortality rate from age 100 d until recruitment at an average age of 5 years was Z = 4.85 (Savoy and Crecco 1988).

These mortality and survival estimates, from annual stockings for juveniles (Table 3) and for larvae (Table 4), were used to calculate the expected recruitment to the spawning runs at an average age of 5 years. For each 1 million larvae which have been stocked above the four hydroelectric plants, about 400 can be expected to return as adults. In terms of absolute numbers, this level of return amounts to an average of 5.6 ± 2.21% of the estimated year-class strength from 1977 through 1985 (Figure 4).

Estimates of observed proportions of hatchery-reared American shad adults returning to the Conowingo Dam have been made by Hendricks et al. (1992a). Hatchery fish have been successfully marked with oxytetracycline beginning in 1986 and fish stocked before 1986 can be distinguished from wild fish by their smaller otolith increment widths (Hendricks et al. 1991b; 1992a). Examination of otoliths from shad captured in the fish lifts at Conowingo Dam during the spring spawning runs of 1989-1991 produced estimates of 18% to 27% wild (non-stocked) shad (Hendricks et al. 1991b; 1992a). Correction of these estimates to account for errors in identification (Maryland Tidewater Administration in-file data) produced estimates of 29% to 31% wild fish for these 3 years. Absolute numbers per year-class of returning adult American shad which were hatchery-reared are presented in Figure 5, along with absolute numbers of expected hatchery-reared adults as calculated above for comparison.

Discussion

The recent exponential growth in year-class strength and the higher ratios of recruitment to spawning stock (compared to the Connecticut River) are consistent with the hypothesis that stocking has had a detectable effect on population growth in the upper Chesapeake Bay. Spawning stock size has also increased at an exponential rate since 1980 (Markham and Weinrich 1994). However, these growth rates could also have been produced solely by the moratorium.

TABLE 3.— Estimated recruitment from fingerlings stocked from 1977 to 1991 assuming that the mortality rate was equivalent to that from the Connecticut River (Savoy and Crecco 1988). Fingerlings were considered to be 100 d old when stocked except in those years designated by **, which were 70 d old. In 1986, marked *, 18,400 fingerlings were released directly into the turbines at Safe Harbor, so fingerling survival was increased to 0.588.

Year	Number stocked above dams	Number surviving after turbine mortality	Number stocked below dams	Total below dams	Number of age 5 recruits
1977	34,500	15,218	0	15,218	50
1978	6,379	2,813	0	2,813	0
1979	34,087	15,032	0	15,032	50
1980	5,050	2,227	0	2,227	0
1981	23,620	10,416	0	10,416	50
1982	40,700	17,949	0	17,949	100
1983	98,300	43,350	0	43,350	100**
1984	30,500	13,451	0	13,451	50
1985	62,000	27,342	53,000	80,342	200**
1986	61,245*	36,012	0	36,012	100**
1987	81,500	35,942	25,000	60,942	250
1988	74,000	32,634	0	32,634	150
1989	60,350	26,614	0	26,614	100
1990	90,000	39,690	163,000	202,690	900
1991	54,400	23,990	179,000	202,990	900

The likelihood that stocking of late larval shad, as are the shad stocked by the PFBC, could increase recruitment is increased by the findings of Crecco and Savoy (1987b) that year-class strength was proportional to the index of abundance of late larvae. Eighteen day-old larvae are considered late larvae and major environmental effects on year-class strength occur before this stage. We may then expect an increase in numbers of late larvae from stocking to produce a proportional increase in spawning recruitment. However, the proportional increase may be more or less accurate for the Susquehanna stockings depending on two untested assumptions. First, we are assuming that environmental conditions in the two rivers are similar. Secondly, we are assuming that stocks from other basins used for egg sources are as well adapted genetically for conditions in the Susquehanna as the Connecticut River stock is for its conditions. Genetic differences among American shad stocks from different rivers may be important (Bentzen et al. 1989; Rottiers et al. 1992). Larvae from different stocks have had widely differing post-stocking survival to the juvenile stage in the Susquehanna (St. Pierre 1992) raising the possibility of genetic effects.

However, the correlation between year-class strength (recruitment) and numbers of prey stocked may be spurious since both variables are correlated with time (years). Hatchery production has increased over time (Figure 6) and year-class strength may also be increasing since the moratorium of 1980 due to natural reproduction and reduced fishing mortality. Although we found no relation between spawning stock size and the resulting recruitment, a stock-recruitment relation may exist (Walters and Ludwig 1981). In addition to errors of measurement, our analysis used only simple linear regression. A dome-shaped recruitment function could possibly be fitted to these data. However, stock sizes were small during the period used in this

TABLE 4.— Estimated recruitment expected from stockings of American shad larvae in the Juniata and Susquehanna rivers from 1977 to 1991. Estimates were based on mortality rates estimated for Connecticut River shad by Savoy and Crecco (1988) and estimates of turbine mortality for shad juveniles developed by Paul Heisey. An asterisk indicates larvae were stocked downstream of the upper three hydroelectric stations.

Year	Number stocked Juniata River (millions)	Number surviving turbine passage (millions)	Number stocked below dams (millions)	Total below dams (millions)	Number of age 5 recruits
1977	1.0	0.4	0	0.4	400
1978	2.1	0.9	0	0.9	800
1979	0.7	0.3	0	0.3	300
1980	3.5	1.5	0	1.5	1,300
1981	2.1	0.9	0	0.9	800
1982	5.1	2.2	0	2.2	1,900
1983	4.1	1.8	0	1.8	1,500
1984	12.0	5.3	0	5.3	4,500
1985	5.4*	4.1	0.8	3.0	2,600
1986	9.9	4.4	5.1	9.5	8,100
1987	5.2	2.3	4.4	6.7	5,700
1988	6.4	2.8	3.6	6.4	5,500
1989	13.5	6.0	7.6	13.6	11,500
1990	5.6	2.5	3.9	6.4	5,400
1991	7.2	3.2	4.9	8.1	6,900

analysis (1980-1985), suggesting that increased mortality at the higher stock sizes tested is not likely (Table 2).

Calculated estimates of the expected number of returning adults from hatchery-reared American shad larvae and fingerlings are a small proportion of the estimates of year-class strength in spawning runs in the upper Bay (Figure 4; Table 5). Any assumptions necessary for the calculation of expected returns were conservative for mortality. For example, the discrepancy between the actual size of larvae at stocking of 13.1 mm and the assumed size of 19.4 mm suggests that stocked larvae could undergo substantially greater mortality (Houde 1987).

Otolith studies (Hendricks et al. 1991a; 1991b; 1992a) provide strong evidence of substantial returns of stocked American shad. The number of stocked American shad collected in the fish traps at Conowingo Dam alone equal or exceed the estimates of expected returns for the entire upper Bay population (Figure 5). American shad collected in the fish traps were a minority of those in the upper Bay run. For example, in 1991, about 27,000 American shad were collected in the traps but the Petersen estimate for the upper Bay spawning population was 141,049 (95% CI: 123,095 to 163,095). Although the expected returns are only point estimates and have unknown confidence limits, the otolith results suggest that actual returns are higher than the estimates, at least for some year-classes.

Several factors may contribute to the discrepancy between the two estimates. First, the estimate of returning adults may be substantially lower than the actual number returning because mortality of stocked American shad larvae and juveniles in the Susquehanna River and upper Bay has been lower than that of wild larvae and juveniles in the Connecticut River. Crecco and Savoy (1985) showed that survival of American shad larvae was higher in warmer, lower flows later in the spawning period, and the more southerly latitude of the Susquehanna River may increase survival. In addition, any density-dependent mortality operating on

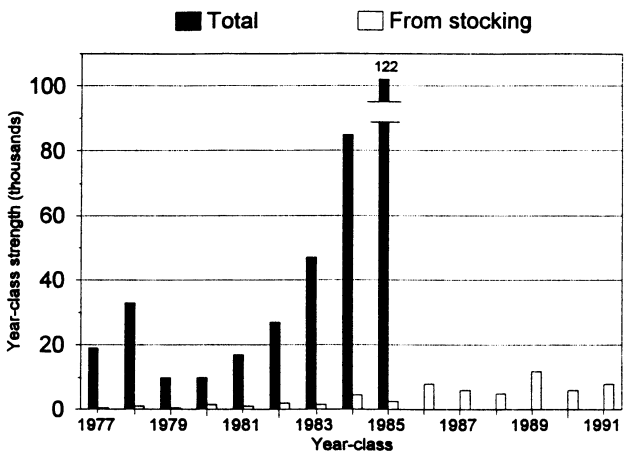

FIGURE 4.—Estimated total recruitment by year-class and expected recruitment from stocking to the spawning run of American shad in the upper Chesapeake Bay.

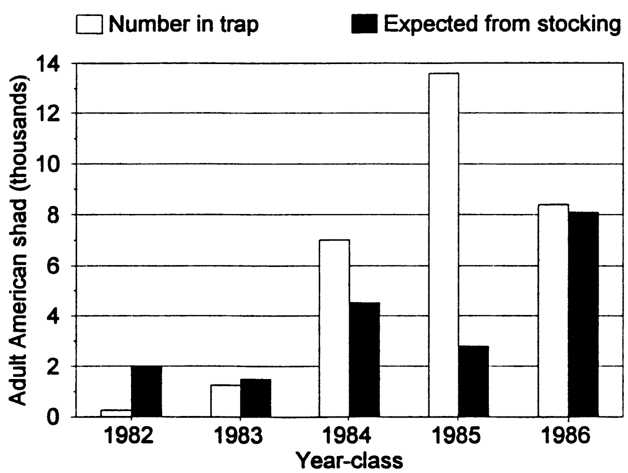

FIGURE 5.—Comparison by year-class of the estimated number of hatchery-reared adult American shad collected in the Conowingo fish traps with the expected total recruitment estimated from stocking. Estimates for the Conowingo lift were calculated from data in Hendricks et al. (1991; 1992) and in RMC (1990; 1991; 1992).

the Connecticut River larvae may be reduced or absent if density is lower for larvae stocked in the Susquehanna River (M. Hendricks, personal communication). Second, we cannot rule out the possibility that the mortality estimates in Crecco and Savoy (1983) were upwardly biased. Their estimates were based on a catch curve of seine-caught shad larvae with the decline in catches of older larvae assumed to indicate mortality. However, this decline may also be due, in part, to reduced catchability of older larvae because of gear avoidance and changes in distribution (S. Minneken, personal communication). If this is true, the mortality estimates will be too high. Third, the fish traps may not collect a random sample of the entire upper Bay spawning population, possibly being biased

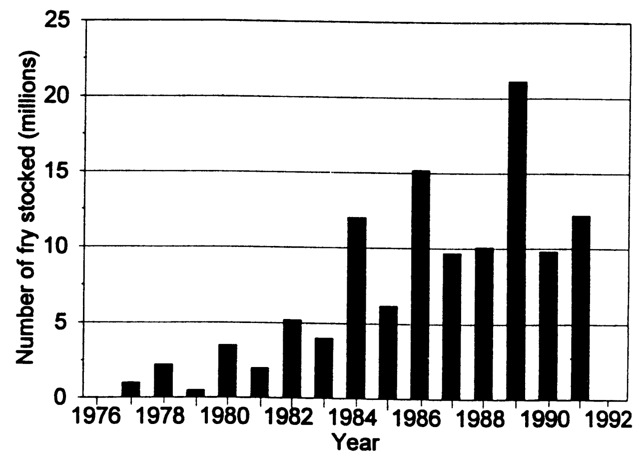

FIGURE 6.—Time series of the number of American shad fry (larvae plus fingerlings) stocked in the Susquehanna River by the PFBC.

towards stocked shad. There may well be behavioral differences between stocked and wild American shad in the upper Bay population. American shad spawn several miles downstream of the Conowingo Dam (Weinrich, personal observation). Radiotelemetry studies, carried out in 1980 when the trap was collecting virtually no shad, indicated that shad staged near Port Deposit and moved upstream a short distance to a spawning area each day, later dropping back to the staging area. Approximately 2% migrated to the tailrace area during the study (M. Hendricks, personal communication). Imprinting of American shad larvae occurs over the first 30 days of life (M. Hendricks, personal communication). Larvae that were stocked in the Juniata River (Table 4) should have imprinted on that river and would probably attempt to return there, congregating in the Conowingo tailrace. Adult American shad trucked above the four hydroelectric plants into the Susquehanna below Harrisburg have been observed spawning in the Juniata River (M. Hendricks, personal communication) indicating they have imprinted on this river. Wild shad spawned in the river downstream of Conowingo Dam should have imprinted on this area and may not attempt further upriver migration. Consequently, native wild shad spawning in the lower river may be under-represented in the tailrace.

If a Petersen estimate for the population in the Conowingo tailrace is calculated using only American shad marked from hook and line, it will be substantially lower than that calculated for the upper Bay population as a whole. For 1989, the tailrace estimate was 42,516 versus 75,329 for the entire population (Weinrich et al.1990); for 1990, the tailrace estimate was 60,541 versus 125,574 for the entire population (Weinrich et al. 1991); and for

Table 5.— Estimated total number of adults recruited to spawning runs (from larvae and juveniles combined), estimated year-class strength, and proportion of observed year-class estimated to be from stocking. (? = unknown).

Year	Estimated number of adults from stocked larvae	Estimated number of adults from stocked juveniles	Estimated total number of adults from stocking	Estimated total recruits from year-class	Percent estimated recruits due to stocking
1977	400	50	450	18,000	2.5
1978	800	0	800	31,000	2.6
1979	300	50	350	9,000	3.9
1980	1,300	0	1,300	8,000	16.2
1981	800	50	850	16,000	5.3
1982	1,900	100	2,000	24,000	8.3
1983	1,500	100	1,600	45,000	3.6
1984	4,500	50	4,550	81,000	5.6
1985	2,600	200	2,800	125,000+	2.2
1986	8,000	100	8,200	?	
1987	5,700	250	5,950	?	
1988	5,500	150	5,650	?	
1989	11,500	100	11,600	?	
1990	5,400	900	6,300	?	
1991	6,900	900	7,800	?	

1991 the tailrace estimate was 84,122 versus 141,049 for the upper Bay (Weinrich et al. 1992). These estimates suggest that a substantial proportion, from 20% to 50% of the upper Bay population, does not migrate all the way to the tailrace. This is consistent with the hypothesis of behavioral differences between native and stocked fish within the upper Bay population.

The results of otolith analysis of adults from the Conowingo trap (Hendricks et al. 1992a) is also consistent with this hypothesis. Because imprinting may continue for the first 30 days of life, 18 d old larvae stocked below Conowingo may imprint on the lower river, or at least may not imprint on the Juniata. Since 1986, larvae stocked downstream of Conowingo (Table 4) were given a distinctive double tetracycline mark which can be detected in the otoliths of adults. These double-marked fish have been relatively rare in adult samples collected in the Conowingo traps. Although 40% of fry stocked from 1986 through 1989 were stocked below Conowingo, they made up only 3% of the 1991 adult sample collected in the Conowingo traps. Although this low proportion could be due to low survival of transport to the stocking site (M. Hendricks, personal communication), transport mortality may be counteracted by the lack of turbine mortality. Otolith analysis of juvenile shad collected in the Susquehanna Flats during the summer and fall has shown that roughly half were wild and half were stocked below Conowingo, suggesting that larvae can survive transport.

Successful reproduction of mature stocked fish is a potential contribution of stockings to population growth which we have not considered. MtDNA analyses have estimated that the proportion of non-native American shad is higher than the proportion of stocked fish estimated by otolith analysis (B. Brown, personal communication). This difference could be due to reproduction of stocked fish, thus increasing the proportion of genetically non-native shad. Because these offspring of stocked fish are wild, however, their otoliths would be indistinguishable from wild native stock, thus producing the observed difference between the two estimates.

At present, our calculation of the expected returns from stocking suggests that the actual proportion of the upper Bay American shad population originating from stocking may be lower than the approximately 70% estimate obtained from otolith analyses of fish sampled from the Conowingo fish traps.

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Maryland's Upper Chesapeake Bay American Shad Survey: An Overview

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Abstract.—On April 4, 1980, a moratorium on sport and commercial fishing for American shad *Alosa sapidissima* in Maryland waters of the Chesapeake Bay was imposed and remains in place today. Since 1980, the Maryland Department of Natural Resources has monitored the adult American shad present in the upper Chesapeake Bay during the spring spawning season. Petersen population estimates have increased exponentially since 1980 and catch per unit effort values for hook and line and fish lift have also increased significantly. Eliminating harvest and increased stocking of juvenile American shad appear to have had a positive influence on stock size. However, our average annual mortality estimates (all gear combined, 1985-1992) of 85.5% for males and 71.5% for females were relatively high for a fishery under a statewide (excluding Atlantic Ocean) moratorium. The process of transferring spawning adult American shad upstream from Conowingo Dam, and the spring ocean-intercept fishery for American shad at the mouth of Chesapeake Bay needs further examination to determine their effects on stock size. Since relaxing restrictions on commercial and recreational harvests may slow or stop recovery, Maryland's Chesapeake Bay American shad moratorium should remain intact to further increase the reproductive potential of upper Bay American shad stocks.

American shad *Alosa sapidissima* and hickory shad *A. mediocris*, as well as alewife *A. pseudoharengus* and blueback herring *A. aestivalis*, have all played an important role in the economic and cultural development of the Chesapeake Bay. Alewife and blueback herring use in Chesapeake Bay was recorded as early as 1680 and, during the American revolution, American shad was a prominent food source for the military. From the late 1800's to mid-1900's, American shad were the most economically valuable food fish harvested from Chesapeake Bay. However, commercial landings of American shad and river herring have steadily declined since the 1930's. By 1980, American shad were so severely depleted that a statewide moratorium on their capture and sale in Maryland waters (excluding the Atlantic Ocean) was implemented to prevent extinction. Similar action was taken in 1981 for hickory shad.

Since previous regulation of these fisheries did not effectively address management needs, the Maryland General Assembly and the Department of Natural Resources responded by initiating several priority actions. These actions included 1) participation in the development, implementation, and revision of an East Coast Alosid Management Plan (ASMFC 1985); 2) the preparation of a Chesapeake Bay Alosid Management Plan (Chesapeake Executive Council 1989); and 3) expanding *Alosa* research and monitoring efforts. The effectiveness of both interstate and Chesapeake Bay management plans is contingent upon the quantity and quality of data that can be provided by this continuing research.

A primary objective of Maryland's anadromous *Alosa* monitoring project is the estimation and characterization of American shad stocks in the upper Chesapeake Bay. This information is vital to the efforts to restore American shad runs to the upper Susquehanna River for two reasons. First, population estimates and stock characterization provide numeric values with which to evaluate restoration progress below Conowingo Dam and the effect of subsequent construction of fish passage facilities at the three hydroelectric stations above Conowingo. Secondly, Strategy 1.1.1 of the Chesapeake Bay Alosid Management Plan (Chesapeake Executive Council 1989) recommends not removing the American shad moratorium in Maryland waters until the upper Bay stock is fully recovered. No fishery would be permitted until this population increases for three consecutive years and stock size reaches 500,000 fish (50% of historical levels) during one of the three years. Then upon reopening, the fishery will continue to be monitored so that initial annual exploitation does not exceed 10%.

Methods

Field Operations

Since 1980, adult American shad have been collected for marking and life history data. Collection has been accomplished with the following four gear types:

Anchored Gill Net. From 1980 through 1987, anchored gill nets were fished in May approximately five miles from the mouth of the Susquehanna River, near the town of Port Deposit (Figure 1). During these eight years, various net lengths and widths, and mesh and twine sizes were employed in order to maximize catch. Generally, net lengths varied from 500 to 1,000 feet and from 6 to 8 feet in depth. Twine sizes used were 69, 104, and 139, while stretched-mesh sizes employed were 4, 4 1/2, 5, 5 1/4, 5 1/2, and 6 inches. Anchored nets were set between 2200 and 2400 hours, when generation from Conowingo Dam was reduced, and were fished until first light. In order to reduce gill net induced stress, the nets were continuously tended. Upon capture, each fish was removed and placed in a fiberglass holding tank 48 inches in diameter and 30 inches deep equipped with a 1,750 gal/h bilge pump to create a strong circular current. Immediately after each net was checked, the fish were transported to deep water, tagged, and released away from the net in order to avoid immediate recapture. Because of the size-selective bias associated with anchored gill nets, the use of this gear was discontinued in 1988.

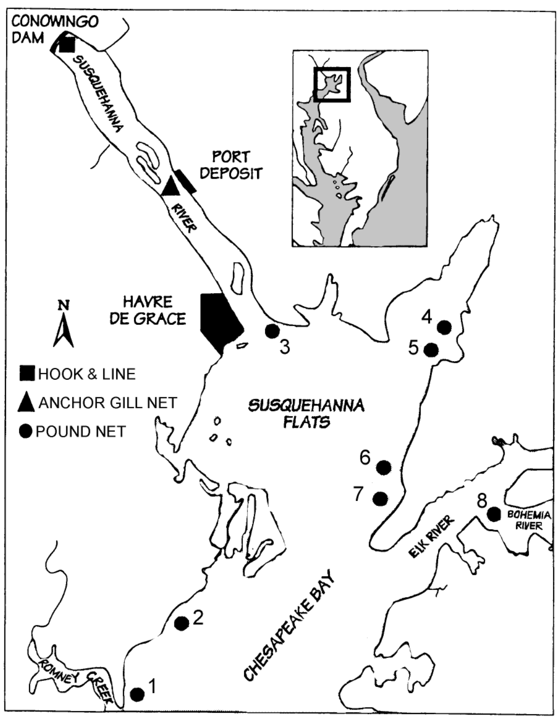

FIGURE 1.—Gear and locations utilized in capturing adult American shad from the upper Chesapeake Bay and lower Susquehanna River, 1980-1992. Pound net locations are 1-Romney Creek; 2-Cherry Tree Point; 3-Perry Point; 4- and 5-Cara Cove; 6-Rocky Point; 7-Beaver Dam; and 8-Bohemia River.

Pound Net. Since 1980, pound net sampling in the upper Chesapeake Bay was done in conjunction with commercial fishing from mid-March through mid-May. Catches of American shad were incidental as this gear was directed at harvesting other species such as channel catfish *Ictalurus punctatus*, striped bass *Morone saxatilis*, Atlantic menhaden *Brevoortia tyrannus*, alewife, and blueback herring. Hence, pound net numbers and locations used to capture adult American shad in the upper Bay have varied since 1980 (Figure 1; Table 1). Normal fishing procedure was to close the funnel door, enter the crib at the heart end, and purse the crib toward the outside wall. After the crib had been pursed, fish were removed by dip net, tagged, and released. Small back-logs of fish could be accommodated by using small aerated drums for temporary holding. However, large numbers of American shad (>30) necessitated tagging only a sub-sample and counting and immediately releasing the rest.

Hook and Line. Hook and line capture of American shad began in 1980, and occurred in the tailrace area below Conowingo Dam from mid-April through the first week in June (Figure 1). With the help of two longtime recreational fishermen, several "hotspots" were identified that historically yielded large numbers of American shad to anglers. Movements of American shad into these "hotspots" was predicated by turbine generation schedules which affect river velocity and depth - two important factors in American shad angling success. Normal procedure was to anchor at different "markers", depending on turbine generation, and fish two rods. Each rod was rigged with two shad darts, one 1/8 oz and one 1/4 oz, with 1/4 to 1/2 oz lead weight added to achieve proper depth. Dart color was restricted to red heads with white or yellow bodies and white or yellow tails. Length of line fished varied depending on fish-holding patterns. Angled American shad were retrieved, tagged, and released as quickly as possible.

Fish Lift. The Philadelphia Electric Company has operated a fish passage facility (West Lift) at its Conowingo Hydroelectric Station since 1972. An additional lift (East Lift) was constructed and operated by spring 1991 to further aid in the restoration of American shad to the upper Susquehanna River (SRFRAC 1992). Lift operations started on 1 April and continued until mid-June and were conducted at least hourly throughout the day depending on the number of American shad collected. Water velocities at the entrances and within the crowder channel were established to maximize American shad catch.

TABLE 1.— Pound net locations used to capture adult American shad in the upper Chesapeake Bay, 1980-1992. Numbers correspond to circled locations on Figure 1.

	Locations							
	Perry Point	Cara Cove		Rocky Point	Cherry Tree Point	Romney Creek	Beaver Dam	Bohemia River
Year	3	4	5	6	2	1	7	8
1980	•	•	•	•				
1981				•	•			
1982				•	•			
1983								
1984								
1985					•			
1986								
1987					•			
1988					•	•	•	
1989					•	•		•
1990					•	•		
1991					•	•		•
1992					•			•

Fish were dip-netted from the sorting tank and most were trucked upstream of the uppermost hydroelectric project (York Haven) on the Susquehanna River.

Data collection. All adult American shad, except those in extremely large catches, collected by anchored gill net, pound net, and hook and line were sexed, their fork lengths measured to the nearest millimeter, and scales removed for later age and spawning history analysis. Weights were recorded from dead fish only and tagging was restricted to those fish which appeared in good condition. Fish were marked with a numbered T-bar anchor tag (Floy model FD-68B) which was inserted into the dorsal musculature posterior to the dorsal fin at an angle conducive to streamlining. Fish were tagged, and possibly recaptured, from upper Bay pound nets from March through May and from mid-May to the first week in June during the hook and line survey in the tailrace below Conowingo Dam. The fish lifts were operated from April 1 until June 15; therefore, recaptures were collected within this period.

Statistical Analyses

Abundance. Chapman's modified Petersen estimate (Ricker 1975) was used to estimate the number of adult American shad returning to the upper Chesapeake Bay each spring because it is statistically unbiased in most situations when the number of recaptures is small (less than 10):

$$N = (M + 1)(C + 1)/ (R + 1)$$

where N is the adjusted Petersen population estimate; M is the number of fish marked; C is the number of fish examined in the recapture sample; and R is the number of marked fish that are recaptured.

Seven basic assumptions need to be met when using the Petersen mark-recapture method of population estimation in order to yield statistically unbiased estimates (Young et al. 1988):

1. *Marked and unmarked fish suffer the same mortality.* Studies on American shad in the Connecticut River indicated some differential mortality as a result of handling and tagging (Leggett 1976). Leggett noted a significant increase in mortality among fish tagged in poor condition. Upper Bay adult American shad were handled carefully and quickly to minimize mortality due to the capture and mark procedure and only fish in good condition were tagged.

2. *Marked and unmarked fish are equally vulnerable to fishing or sampling.* Differences in behavior resulting from tagging, or from the effect of the tag, might increase the vulnerability of the fish to be captured (Leggett 1976). After analyzing upriver migration rates determined by conventional tagging, Leggett's data suggested that after being tagged with a spaghetti-dart tag, American shad delayed their upriver migration for approximately 10 days. However, most fish imprinted to spawn in the upper Susquehanna River would eventually reach the dam.

3. *Marked fish do not lose their marks.* Leggett (1976) calculated an annual rate of 3% for tag shed-

ding for American shad in the Connecticut River. Therefore, the number of fish marked was reduced by 3% to eliminate any error associated with tag shedding. Tag returns in 1992 from fish marked as far back as 1987 suggested that tag retention was good and could extend past the seasonal recapture period.

4. *Marked fish either become randomly mixed with unmarked fish or the recapture samples are selected randomly from the entire population.* The assumption that tagged individuals were distributed at random within the population may not be valid immediately after a tagging session when both marking and recapturing were happening simultaneously. Seber (1982) suggested an appropriate time period be allowed for tagged individuals to become randomly distributed throughout the population. Mean days-at-large for a marked fish to be recaptured have ranged from 7-21 since 1980.

5. *All marked fish in the recapture sample are recognized.* Errors due to missed marks should be negligible as experienced personnel from the Maryland Department of Natural Resources (MDNR) and Radiation Management Corporation (RMC) were responsible for tag recognition and reporting.

6. *Recruitment to the population is negligible during the mark-recapture study.* The assumption of constant recruitment is seldom satisfied, particularly for short-lived *Alosa* species (ASMFC 1988). Furthermore, since recoveries were being made over a considerably short period of time (March through mid-June), the effect of recruitment should be negligible.

7. *No emigration occurs from the study area (the system is closed).* Since several recaptures occur outside the upper Chesapeake Bay system each year, a percent adjustment for emigration was also included in the Petersen estimate to account for fish lost and unavailable for later recapture, and for fish which may leave the Bay immediately after spawning. This adjustment takes into account only pound net tagged fish since they were the only fish that had been recaptured outside the system.

The upper Chesapeake Bay American shad population estimates (1980-1992) were analyzed using an exponential population growth equation (Poole 1974). The equation of this curve was:

$$N_t = N_o e^{rt}$$

where t 0 and N_t is the number of individuals in the population at time t; N_o is the population density at time t = 0; and r is the instantaneous intrinsic rate of population increase. This model was then transformed into a linear model by taking natural logarithms ($\ln N_t = \ln N_o + rt$; Younger 1985).

Relative abundance, measured as annual catch per unit effort (CPUE) of upper Bay American shad collected by pound net, hook and line, and fish lift, was calculated as an arithmetic mean, where total catch was divided by total effort and expressed as fish caught per pound net day, fish caught per boat hour, or fish caught per lift hour.

Kendall's coefficient of rank correlation was used to explore associations among arithmetic mean annual CPUE's (1985-1992) of American shad captured by pound net, hook and line, fish lift, and the Petersen population estimates. This test was chosen because the mean annual CPUE's were not normally distributed.

Mortality. In past years, both the Robson-Chapman method and a standard catch curve analysis were used to estimate annual mortality. However, according to Ricker (1975), the Robson-Chapman method is acceptable only when the following assumptions are met: a) recruitment is constant among years; b) survival among age-classes is constant; and c) vulnerability of all ages to the sampling gear is equal. Since it cannot be assumed that adult recruitment was constant, the Robson-Chapman method for estimating mortality was not appropriate for American shad. Furthermore, this method, as well as a standard catch curve analysis, assumed a random sample of the population. However, only the American shad spring spawning run was sampled; proportions of year-classes sexually maturing each year vary because American shad from a given year-class tend to initiate spawning over a range of years (ages 3-7: Leggett 1969). Calculation of mortality estimates using catch curves should be limited to repeat spawners (Ricker 1975). Therefore, total annual mortality was estimated using Crecco and Gibson's method (ASMFC 1988), where $\log_e$-transformed spawning group frequency was regressed against corresponding number of times spawned (assuming that consecutive spawning occurred):

$$\log_e (S_{fx} + 1) = a + Z * W_{fx}$$

where S_{fx} is the number of American shad with 1, 2,...f spawning marks in year x; W_{fx} is the frequency of spawning marks (1, 2,...f) in year x; and Z is the instantaneous mortality.

Beginning with the first age group in which practically no virgin fish occurred, the abundance of successive ages from there on should reflect the population survival rate between them. The validity of using this method for estimating Z depends on the assumptions that both fishing and natural mortality rates are constant over all ages and population sizes, and that recruitment to the spawning population is constant (Ricker 1975).

Instantaneous mortality (Z) was estimated separately for males and females since females are larger and generally mature later than males (Leggett 1969). Total annual mortality (A) was calculated as 1 - e^{-z}. An average total annual mortality was also calculated (1984-1992) for male and female upper Bay American shad. This calculated rate only applied to fish which had spawned at least once.

Length-at-age. American shad mean lengths-at-age were calculated to the nearest millimeter for each sex, gear, and year (1984-1992). A two-factor analysis of variance (ANOVA) was used to determine if mean lengths-at-age for American shad captured in 1992 by the fish lifts and aged by RMC at Conowingo Dam differed from mean lengths-at-age for American shad captured by pound net and hook and line and aged by MDNR. The GLM procedure of SAS was employed because of an unbalanced design (SAS 1988).

For each year between ages 3 and 7, lengths of American shad (all gear combined 1984-1992) were analyzed with linear regression models to determine trends over time. Males and females were analyzed separately because females tend to be larger at age than males.

Maturity. The arcsine-transformed proportions of male and female American shad repeat spawners collected (gears combined, 1980-1992) were analyzed with linear, quadratic, and cubic regression models to determine trends in time (Sokal and Rohlf 1981).

Age Composition. Effects of gear type on sex ratio and age structure of American shad were examined using a logistic regression with categorical variables. This model provides a goodness-of-fit statistic rather than an F-test, and is comparable to ANOVA and multiple regression for categorical (attribute) data. It is an analysis of frequencies involving three or more factors and is primarily used in testing for the presence of interactions (Sokal and Rohlf 1981).

Results

Abundance. The number of fish marked (M), the number in the recapture sample (C), and the number recaptured (R) were used in calculating Petersen population estimates for upper Chesapeake Bay American shad collected in 1980-1992 from anchored gill nets, pound nets, hook and line, and the Conowingo fish lifts (Table 2). The adult American shad Petersen population estimate in 1992 was 105,255 (95% confidence intervals: 87,396-126,725). These population estimates have increased exponentially since 1980: $N_t = 5{,}014\ e^{0.294t}$ ($r^2 = 0.79$, $P < 0.001$; Figure 2).

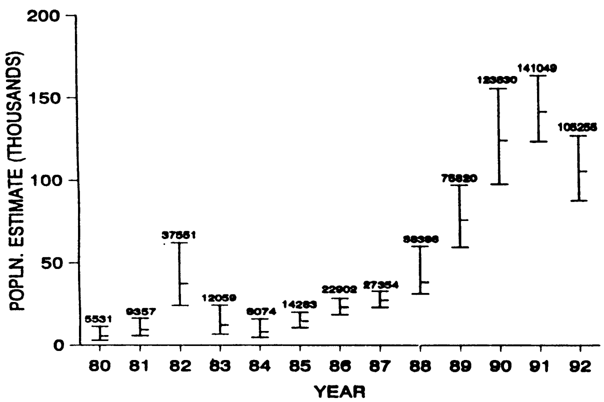

Figure 2.—Petersen population estimates of adult American shad in the upper Chesapeake Bay, 1980-1992. Bars indicate 95% confidence ranges of the estimates and numbers above them indicate the yearly population estimate.

Estimates of hook and line (1984-1992) and fish lift (1983-1992) CPUE have increased linearly over time (hook and line: $r^2 = 0.73$, $P < 0.003$; lift: $r^2 = 0.81$, $P < 0.0001$; Figure 3). Pound net CPUE showed no linear trend ($r^2 = 0.05$, $P < 0.65$). Kendall rank correlations indicated that hook and line CPUE was correlated ($r_k = 0.56$, N = 9, $P < 0.04$) and fish lift CPUE was highly correlated ($r_k = 0.87$, N = 10, $P < 0.0005$) with the Petersen population estimate whereas pound net CPUE showed only a marginal correlation with the Petersen estimate ($r_k = 0.52$, N = 7, $P < 0.10$). Individual CPUE's for each gear type showed no correlation with each other (Table 3).

Mortality. Total mortality estimates (all gear combined) for mature upper Bay American shad in 1992 equaled 72.3% for males and 79.0% for females. The average annual total mortality estimate for the years 1985 to 1992 was 85.5% (SE = 2.28; 95% confidence interval: 80.1-90.9) for males and 71.5% (SE = 5.04; 95% confidence interval: 59.6-83.4) for females (Figure 4).

Lengths-at-age. Upper Bay female American shad mean lengths-at-age were greater than corresponding mean male lengths-at-age. Male and female American shad lengths-at-age were not influenced by gear type. Mean lengths-at-age for fish captured by pound net and hook and line were not significantly different than mean lengths-at-age for fish captured by the Conowingo fish lifts.

TABLE 2.— Total number of American shad caught and tagged from upper Chesapeake Bay pound nets (PN) from mid-March through mid-April 1980-1992, anchored gill nets (AGN) during May 1980-1987, hook and line (H&L) from late April to the end of May 1982-1992, and the Conowingo Dam fish lifts (LIFT) from 1 April to 15 June 1983-1992. For each yearly Petersen estimate, the number in the recapture sample (C), number of fish marked (M), and number recaptured (R) have been adjusted for emigration and 3% tag loss.

Year	Gear	Number of shad tagged	Number of shad caught	C	M	R
1980	PN	120	89	379	130	8
	AGN	144	65			
	LIFT	139				
1981	PN	65	65	604	231	9
	AGN	229	186			
	H&L	1	1			
	LIFT	317				
1982	PN	79	76	2413	279	17
	AGN	259	182			
	H&L	82	81			
	LIFT	2039				
1983	PN	1	0	576	214	9
	AGN	214	207			
	H&L	11	10			
	LIFT	413				
1984	AGN	125	122	414	220	10
	H&L	126	99			
	LIFT	167				
1985	PN	33	30	1836	310	39
	AGN	141	134			
	H&L	173	156			
	LIFT	1546				
1986	AGN	107	69	5532	326	78
	H&L	437	267			
	LIFT	5195				
1987	PN	9	7	8019	381	111
	AGN	73	54			
	H&L	398	329			
	LIFT	7667				
1988	PN	170	136	5585	297	38
	H&L	256	228			
	LIFT	5169				
1989	PN	400	298	8953	524	61
	H&L	276	261			
	LIFT	8311				
1990	PN	399	286	1666	534	71
	H&L	309	295			
	LIFT	15964				
1991	PN	1054	641	28624	942	192
	H&L	437	396			
	LIFT	27227				
1992	PN	190	114	26253	440	109
	H&L	383	353			
	LIFT	25721				

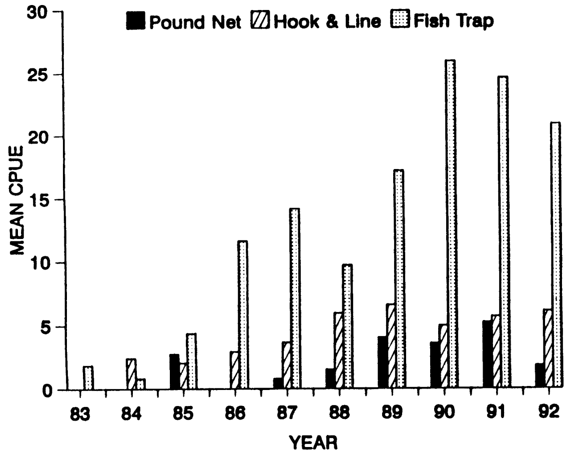

Figure 3.—Estimates of annual catch per unit effort (CPUE) for upper Chesapeake Bay American shad captured by pound net (fish/pound net day), hook and line (fish/boat hour), and fish trap (fish/trap hour), 1983-1992.

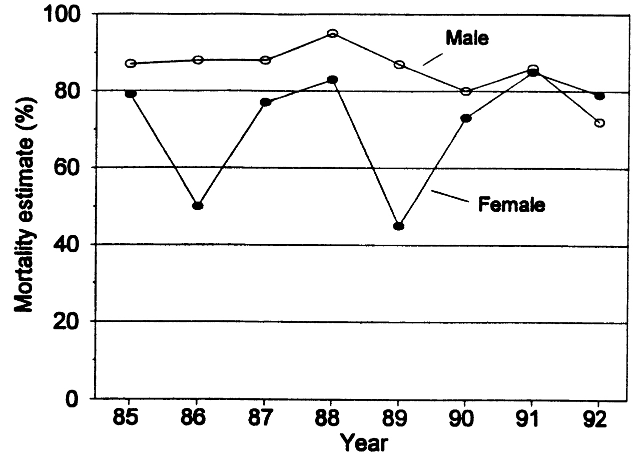

Figure 4.—Estimates of annual percentages of total mortality (all gear combined) for upper Chesapeake Bay male and female American shad, 1985-1992.

Lengths of male and female American shad decreased significantly over time (1984-1992, all gear combined) for each age between 4 and 7 (Figures 5 and 6; Table 4). The r^2 values were relatively low because individual lengths were used rather than means.

Maturity. The arcsine-transformed proportions of male and female American shad repeat spawners (all gear combined) showed no linear, quadratic, or cubic trend over time (1980 to 1992; Figures 7 and 8; Table 5).

Age Composition. Age frequency of American shad captured by pound net, hook and line, and fish lift in 1992 was used to determine if differences existed between gear types (Table 6). A logistic model with categorical variables of gear, sex, and age found no interaction between gear type and sex ratio. Therefore, the proportion of male and female American shad captured was not affected by the type of fishing gear used. However, a significant interaction was found between gear type and age structure. A model containing this interaction gave the best fit (test for lack of fit: G = 8.90, df = 12, NS). Hook and line catches were comprised of greater proportions of 2-5 year-old fish than pound net and fish lift catches. Conversely, pound net catches showed a greater proportion of 6-8 year old fish than hook and line catches, thus confirming the

TABLE 3. — Kendall's coefficient of rank correlation (r_k) for the annual Petersen population estimate and annual arithmetic mean CPUE for three gear types used to capture American shad in the upper Chesapeake Bay (N = number of years).

	Petersen Population Estimate	Pound Net	Hook & Line	Fish Trap
Petersen Population Estimate	1.000 N=13 —			
Pound Net	0.524 N=7 *P* = 0.099	1.000 N=7 —		
Hook & Line	0.556 N=9 *P* = 0.037	0.238 N=7 *P* = 0.453	1.000 N=9 —	
Fish Trap	0.867 N=10 *P* = 0.0005	0.333 N=7 *P* = 0.293	0.389 N=9 *P* = 0.144	1.000 N=10 —

TABLE 4.— Regression statistics for male and female American shad lengths-at-ages captured in the upper Chesapeake Bay (all gear combined), 1984-1992. (N = sample size, Y = mean length and X = time in years).

Age	N	Regression equation	r^2	P
Male				
4	1461	Y = 577.90 - 2.23 X	0.03	0.0001
5	1432	Y = 912.33 - 5.55 X	0.09	0.0001
6	486	Y = 1,447.86 - 11.10 X	0.12	0.0001
7	58	Y = 1,634.65 - 12.82 X	0.12	0.008
Female				
4	354	Y = 552.13 - 1.52 X	0.02	0.02
5	1247	Y = 985.73 - 6.00 X	0.14	0.0001
6	1092	Y = 1,276.99 - 8.89 X	0.16	0.0001
7	341	Y = 1,242.56 - 8.09 X	0.10	0.0001

assumption that pound nets tend to select for older, larger fish (Ricker 1975). Age structure in fish lift catches appeared to more closely resemble pound net catches.

Discussion

Upper Chesapeake Bay American shad populations have been increasing exponentially since 1980, but are still low when compared to historical levels. Catch per unit effort (CPUE) has been increasing for both the fish lift and hook and line. No time trend was evident for pound net CPUE because capture efficiency with a passive gear is primarily a function of fish movement and there are several important environmental variables such as season, water temperature, water level, turbidity, and currents which influence movement tendencies

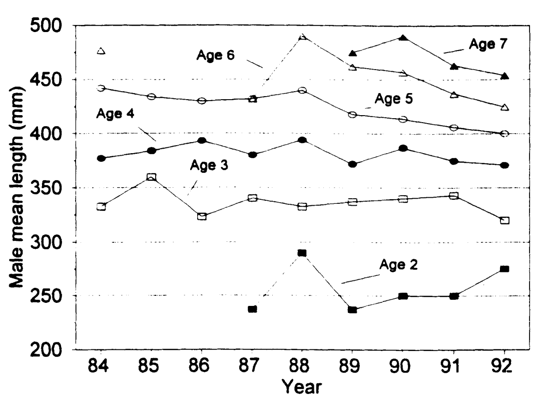

FIGURE 5.—Mean lengths of male American shad captured in the upper Chesapeake Bay (all gear combined) over time (1984-1992) for ages 2-7.

(Hubert 1983). The number of American shad fry stocked in the upper Chesapeake Bay has increased through time (1977-1992), and year-class strength (1977-1984) was highly correlated with numbers of fry stocked (Kahn and Weinrich 1994), which further supports the increase in the upper Bay population estimates.

Due to the size selective bias associated with anchored gill nets, this gear was discontinued in 1988. Therefore, greater emphasis was placed on upper Bay commercial pound nets for American shad capture. This increased use of pound nets may have affected the upper Bay population estimates. The 1988 Petersen population estimate did show an increase when pound net effort was increased; however, the estimate has continued to increase exponentially since then. Pound nets in the Susquehanna Flats sample a larger portion of the upper Bay than anchored gill nets set in the Susquehanna River, and consequently have a better chance to catch fish. Therefore, the total upper Chesapeake Bay American shad population may be more accurately estimated by pound net sampling. However, a portion of these fish may not attempt to migrate to Conowingo Dam. For instance, in 1980, wild American shad were staged near Port Deposit, approximately five miles downstream of Conowingo Dam during a radiotelemetry study. This study indicated that most fish only moved a short distance upstream to spawn each day, and then dropped back to the staging area; only a few fish migrated to the tailrace area (M. Hendricks, personal communication). Therefore, some fish captured and tagged in the pound nets in the Susquehanna Flats may never migrate into the tailrace and thus, may never be recaptured in the fish lifts at Conowingo Dam.

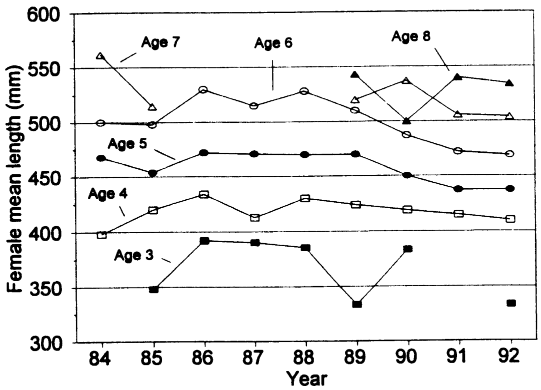

FIGURE 6.—Mean lengths of female American shad captured in the upper Chesapeake Bay (all gear combined) over time (1984-1992) for ages 3-8.

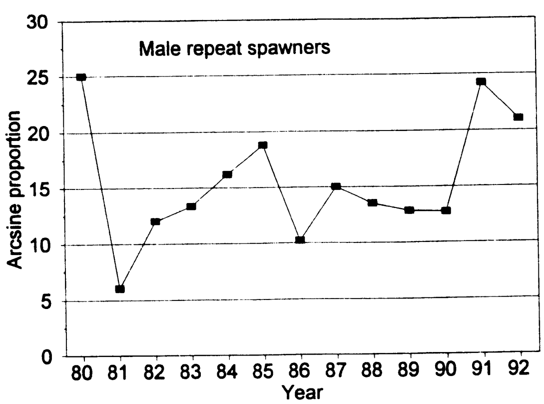

FIGURE 7.—Arcsine-transformed proportions of repeat spawning male American shad collected in the upper Chesapeake Bay (all gear combined) during 1980-1992.

In addition, fish lift and hook and line CPUE's were highly correlated and pound net CPUE was marginally correlated with the upper Bay Petersen population estimates. Bannerot and Austin (1983) determined that catch rates and population abundance can be assumed to be proportional to spawning stock size when the population is small. When populations are large, gear saturation and unequal distribution reduce the reliability of mean catch rate as an indicator of spawning stock size (Bannerot and Austin 1983; Crecco et al. 1983). Since the upper Bay shad populations are small and CPUE values from the three gear types are correlated with population estimates, it would appear that the upper Bay population estimate is proportional to the spawning stock and that corresponding CPUE values reflect trends in American shad stock size in this system.

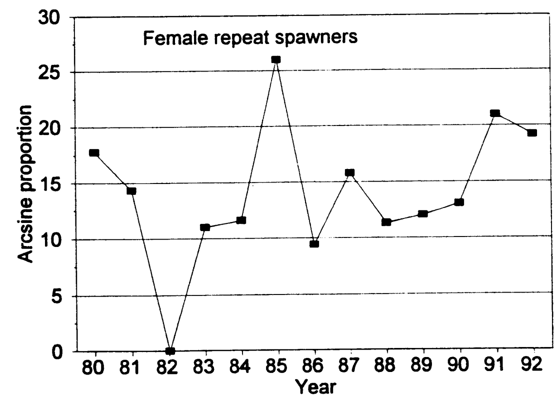

FIGURE 8.—Arcsine-transformed proportions of repeat spawning female American shad collected in the upper Chesapeake Bay (all gear combined) during 1980-1992.

A moratorium on the harvest of American shad in Maryland waters has been in place since 1980. However, estimates of total annual mortality suggest continuing exploitation of the upper Chesapeake Bay stock. The average annual mortality estimate generated for mature, reproducing shad from the upper Bay (1985-1992) was 86% for males and 72% for females. Annual mortality estimates are in close agreement with several other American shad populations subject to fishing. Walburg (1961) reported an average annual mortality estimate of 73% for American shad in the Connecticut River (1956-1959, sexes combined) based on frequencies of age and spawning groups. Similarly, Leggett (1976) calculated average annual mortality rates of 70% for males and 71% for females for Connecticut River American shad (1965-1972) using the method of Royce (1972). Furthermore, PSE&G (1982) estimated American shad mortality rates to be 70-80% in the Delaware River.

Our mortality estimates appear to represent an exploited population even though a statewide moratorium exists on the capture and subsequent sale of American shad in the state. In a commercial or recreational fishery, exploitation would tend to select older, larger fish of a given year-class. When a larger fraction of these larger fish is removed, the result is a smaller estimated size for fish of younger ages than the true average size at the age in question (Ricker 1975). Male and female American shad lengths-at-age have been decreasing over time in the upper Chesapeake Bay (Figures 5 and 6; Table 4). The removal of adult American shad that occurs at the Conowingo Dam fish lifts may be contributing to this decrease. In 1990, 1991, and 1992, the Conowingo fish lifts collected 15,282, 19,911, and 16,932 adult American shad which were subsequently transported to the upper Susquehanna River. It can be assumed that most, if not all, adult

Table 5.— Total catch (N) and percentages (percent repeat) of male and female American shad repeat spawners collected from the upper Chesapeake Bay during 1980-1992 (all gear combined).

Year	Male		Female	
	N	Percent repeat spawners	N	Percent repeat spawners
1980	12	17.9	11	9.4
1981	1	1.1	3	6.1
1982	8	4.4	0	0
1983	4	5.5	7	3.6
1984	17	7.7	7	4.0
1985	53	10.4	51	19.1
1986	24	3.1	6	2.6
1987	38	6.6	22	7.3
1988	21	5.6	12	3.8
1989	33	4.9	15	4.3
1990	34	4.8	34	5.1
1991	169	17.0	127	12.6
1992	53	12.3	65	10.8

fish transported were unsuccessful at passing through the four hydroelectric stations during outmigration and hence, were lost as returning adults. Therefore, this removal may act as a type of "fishing mortality" where the larger, faster-growing members of a year-class become vulnerable to the fish lifts, and decreases in mean lengths-at-age would be evident for subsequent year-classes. The spring ocean-intercept fishery for American shad located at the mouth of the Chesapeake Bay may also be contributing to high mortality rates and associated decreases in mean length-at-age. Since 1984, commercial American shad catches from this fishery have ranged from 332,000 to 644,000 pounds with a nine-year mean of 413,000 pounds. However, we cannot rule out the possibility that these decreases in mean lengths-at-age are the result of density-dependent growth. As year-class strength increases, a building population would have a decreasing trend in mean length (Ricker 1975). However, the fact that younger ages did not show this decline as clearly argues against density-dependent causes.

Despite relatively high total mortality rates for a fishery under a statewide moratorium, American shad stocks in the upper Chesapeake Bay show positive signs of recovering. Harvest restrictions in Chesapeake Bay and increased stocking of juvenile American shad appear to have had a positive influence on stock size. Transferring spawning adult American shad upstream from Conowingo Dam, and the continuing ocean-intercept fishery, may decrease stock size and increase mortality rates. These processes need further examination to fully understand their effects. Since relaxing restrictions on commercial and recreational harvests may slow

TABLE 6.— Age frequency and percentages (in parentheses) of male and female American shad collected from the upper Chesapeake Bay by pound net, hook and line, and fish lift from March to June, 1992.

Age	Pound Net		Hook and Line		Fish Lift	
	Male	Female	Male	Female	Male	Female
2	0 (0)	0	1 (0)	0 (0)	0 (0)	0 (0)
3	1 (0)	0	18 (0)	0 (0)	6 (0)	1 (0)
4	19 (0)	5 (0)	52 (0)	9 (0)	42 (1)	12 (0)
5	31 (4)	30 (0)	90 (6)	88 (1)	91 (12)	101 (12)
6	9 (4)	37 (7)	16 (2)	66 (5)	40 (14)	134 (16)
7	4 (4)	25 (6)	2 (0)	28 (7)	9 (6)	60 (10)
8	0 (0)	1 (0)	0 (0)	1 (0)	0 (0)	4 (1)

or stop recovery, Maryland's Chesapeake Bay American shad moratorium should remain in effect to further increase the reproductive potential of upper Bay American shad stocks.

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Blueback Herring Behavior in the Tailrace of the St. Stephen Dam and Fish Lock

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Abstract.—The St. Stephen hydroelectric dam located on the Rediversion Canal, South Carolina, contains a fish lock in which the vertical lift chamber is flooded to raise fish approximately 15 m to lake level. The entrances to the fish lock are directly adjacent to the discharge of three turbines which generate 84 MW. Preliminary operations showed that fish had difficulty locating the entrances to the fish lock during periods of full generation. Controlled turbine discharges were utilized to examine if passage of blueback herring *Alosa aestivalis* and American shad *A. sapidissima* could be improved with reduced discharges. Average blueback herring passage per lock cycle decreased from 224 to 217 to 23 fish while one, two and three turbines were discharging. Average American shad passage per lock cycle decreased from 285 to 136 to 112 fish while one, two, and three turbines were discharging. A telemetry study on adult blueback herring in the tailrace found that even with reduced discharges, only 12 of 33 tagged blueback herring were recorded near the lock entrances and only one tagged fish was passed through the lock.

Fish passage systems help mitigate problems created by dams which block the migration of diadromous fishes. Fish lifts, fish locks, fishways, and navigation locks provide fish upstream access. However, the success of a fish passage system may be affected by various factors. Fishways constructed at the Holyoke Dam on the Connecticut River, Massachusetts, in the 1870's and 1940's proved unsuccessful at passing American shad *Alosa sapidissima*. Major factors which limited the success of these early fishways were poor entrance locations, insufficient attraction flows, and excessive water turbulence (Rizzo 1969). In 1955, a fish elevator system went into operation at the Holyoke Dam. Although this lift represented the first successful upstream passage facility for American shad at a hydroproject tailrace in the Northeast, numerous modifications were needed to improve its efficiency (Moffitt et al. 1982).

Fishway efficiency depends on fish not being delayed in locating, entering, and passing through the fishway (Clay 1961; Everhart and Youngs 1975). Most delays occur in the tailrace, where turbulence associated with spillage or generation obscures entrance flows and creates eddies which disorient fish (Rainey 1991). Fishway efficiency can be increased by multiple entrances which give considerable operational flexibility during generation or spillage (Everhart and Youngs 1975). Fish should be able to travel quickly through the fishway without being delayed or stressed.

The fish lock at the St. Stephen Dam, located on the Rediversion Canal, South Carolina, was designed to pass primarily blueback herring *Alosa aestivalis* and American shad. The hydroelectric plant delivers peak power on an as-needed basis. A major concern was that fish were not attracted to the St. Stephen fish lock during periods of no water flow and were unable to locate the two lock entrances during full power generation. Turbulence created during full power production (672 m^3/s) masked the 8.68 m^3/s attraction flow emitted through the fish lock: a large number of American shad and blueback herring were present in the tailrace while few were actually being passed through the fish lock.

This paper reports the findings of two studies conducted to identify problems with the entrance design of the St. Stephen fish lock. In 1990, controlled turbine releases were granted by the operating utility company which enabled the effects of various turbine discharges on fish passage to be studied. In 1991, a telemetry study determined blueback herring movements in the tailrace. These studies justified a request for a major redesign of the fish lock.

Methods

The St. Stephen hydroelectric dam (84 MW production), located midway on the Rediversion Canal, rediverts water from the Santee-Cooper lake system back into the Santee River. The facility was completed in 1985 and included a fish lock as mitigation for the anticipated loss of fish passage on the Cooper River (Cooke and Eversole 1994). Three turbines at the facility discharge up to 224 m^3/s each into the Santee River.

In 1990, an agreement was reached with the South Carolina Public Service Authority (SCPSA) to regulate flows at the St. Stephen Dam. During a study from March 9 to April 12, 1990, all three turbines continuously discharged an average flow of 627 m^3/s except during a 9 hour daily period when either one or two turbines were discharging. The number of turbines discharging were altered each day. Fish passage rates were then compared when one and two turbines were discharging.

The turbine nearest the lock entrances (turbine 3) was always one of the turbines that was turned off for the study, except for five days (March 20-21 and 23-25) when all three turbines were constantly discharging due to heavy rainfall. The number of fish passed at this time was used to document fish passage during three-turbine operation.

Fish were visually identified and counted as they passed a viewing window. Counts from two to four personnel were averaged at the end of each counting period. Average fish passage per lock was then compared with turbine discharge. High heterogeneity in the data required that the analysis be done on the ranks of fish passage per lock. Treatments were tested for a significance in variation with a general linear model.

A radio telemetry study of adult blueback herring was conducted from March 12 through April 7, 1991, in the tailrace of the St. Stephen Dam. Blueback herring movements were continuously monitored in the tailrace during various generation discharges from the dam. One or more turbines discharged continuously throughout the telemetry study in conjunction with turbine 3 being off for 10 hours daily for fish passage.

Adult blueback herring were electrofished in the tailrace for the telemetry studies. Radio tags (9 x 29 mm, double battery, 4.2 g weight, 275 mm length coated wire antenna) were orally inserted into the stomachs of 25 adult blueback herring between March 12 and 13. All blueback herring were briefly held onboard to evaluate survival before release. Each radio tag emitted a unique 150 MHz frequency at 60 pulses per minute. Eighteen adult blueback herring were radio-tagged (9 x 24 mm, single battery, 2.8 g weight, 275 mm length coated wire antenna) and released on March 19 along with two blueback herring equipped with the 9 x 29 mm tag. Each of these tags emitted a unique 150 MHz frequency at 90 pulses per minute. All blueback herring were released at water temperatures between 13° and 15°C.

Lotek SRX-400 receivers continuously monitored the movements of the tagged blueback herring (Figure 1) from the south (Receiver 1) and north (Receiver 2) wingwalls. Both receivers were linked to a main antenna and to one or two auxiliary antennas. Two four-element Yagi auxiliary antennas recorded blueback herring that went behind the south (Aux. 1.1) and north (Aux. 2.1) wingwalls. The main antennas covered an area approximately 120 m downstream of the wingwalls as well as the tailrace area between the two wingwalls. Another auxiliary antenna (Aux. 2.2) was suspended over the fish lock entrances to record blueback herring within approximately 5 m of the lock entrances. A 10 m length of insulated wire was also suspended over the lock entrances to ensure that blueback herring actually passing through the lock entrances were recorded. Other receivers were strategically located in the Rediversion Canal to determine the amount of time tagged blueback herring spent in the canal. Further details on these locations can be found in Cooke and Chappelear (1991).

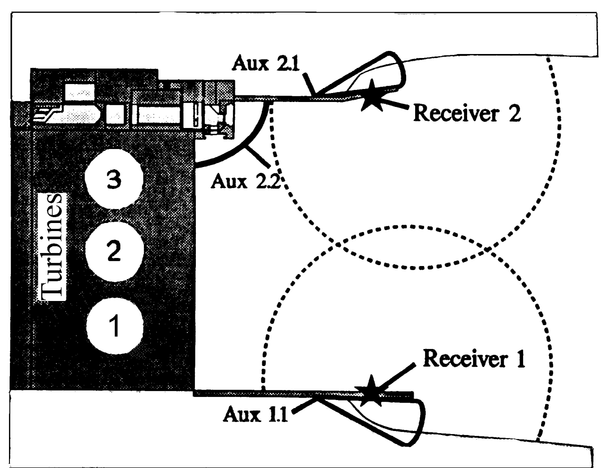

FIGURE 1.—Receiver and antenna locations used to record radio-tagged adult blueback herring in the railrace of the St. Stephen Dam and fish lock. Dashed lines indicate tailrace area recorded by the two main antennas. Solid lines indicate areas recorded by auxiliary antennas.

Daily data were examined for potential false signals such as those produced by outboard motors moving throughout the canal. Signal strength, chronology, and pulse rates verified the validity of the data. The number of fish using a specific area, number of fixes, and average total residency time per fish for the study were summarized. The average time per fish spent at a particular location at various discharges was calculated by dividing the total time spent at a location by the number of fish recorded at that location during a particular discharge. Fixes that were recorded simultaneously by two receivers, due to overlap, were deleted from the data of one receiver. Attempts by blueback herring to move upstream of the dam were defined by the recording of fish entering the area covered by receivers 1 and 2. Upstream movements were concluded when the blueback herring dropped downstream out of this area or went behind one of the wingwalls and was recorded by one of the auxiliary antennas.

Results

Regulated turbine discharges resulted in 15 days of generation each for one and two turbines, and 5 days of generation for all three turbines. Flows averaged 209 m^3/s (SD = 41) with two turbines off and 419 m^3/s (SD = 32) with one turbine off. Blueback herring and American shad passage was higher at both reduced discharges when compared with full generation (Figure 2).

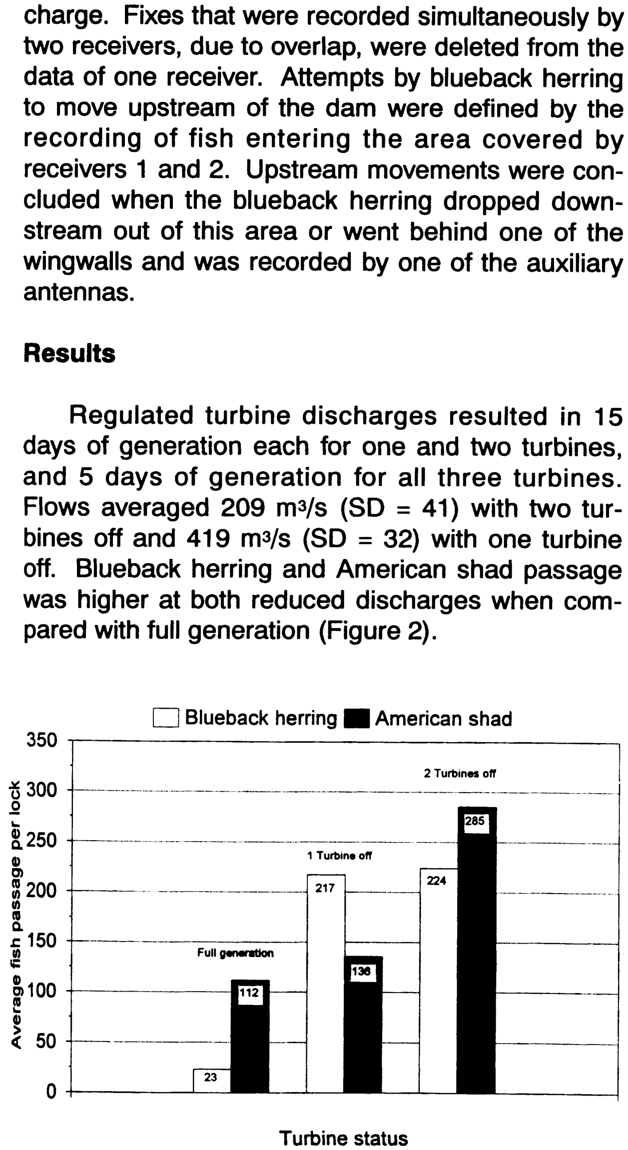

FIGURE 2.—Average number of blueback herring and American shad passed per lock cycle at various discharges at the St. Stephen Dam and fish lock.

Average passage of blueback herring increased from 23 to 217 to 224 per lock cycle with three, two, and one turbines discharging. Significant differences in blueback herring passage existed between the conditions of one turbine off and two turbines off (P = 0.0505) and between two turbines off and full generation (P = 0.0139). Average American shad passage increased from 112 to 136 to 285 per lock cycle when the discharge decreased from three to two to one turbine(s) operating. Significant differences in American shad passage existed between two turbines off and one turbine off (P = 0.0002) and between two turbines off and full generation (P = 0.0031).

The telemetry study illustrated that blueback herring were not readily finding the lock entrances. The results were based on thirty-three of the 45 tagged blueback herring that remained in the Rediversion Canal for more than a day. The remaining blueback herring either left the study area and never returned (n = 8) or became stationary and were presumed dead (n = 4).

Eighteen percent, 52%, 27%, and 3% of the radio-tagged blueback herring remained in the Rediversion Canal for more than 1, 5, 10, and 15 days. Radio-tagged blueback herring spent an average of 8.6 days in the Rediversion Canal. No difference was evident ($P > 0.05$, chi square test) in time spent in the Rediversion Canal between the groups of radio-tagged fish released so the data were pooled.

Receivers 1 and 2 recorded a total of 1601 fixes from 26 different blueback herring in the tailrace area (Table 1). Of these fixes, 12 fish made only 54 fixes in the vicinity of the fish lock entrances. Only one of these fish successfully found an entrance and was passed upstream.

Nine of the 12 blueback herring recorded at the lock entrances remained in the area an average of 25.5 minutes each while turbine 3 was not discharging (Table 2). When all three turbines were discharging, seven of the 12 different blueback herring recorded at the lock entrances remained in the area an average 8.7 minutes each.

TABLE 1.— Number of different radio-tagged blueback herring and the total number of fixes recorded at various antenna locations in the tailrace of the St. Stephen Dam and fish lock.

Location	Fish	Fixes	Fixes per fish
Receivers I and 2	26	1601	61.6
Auxiliary 1.1	16	191	11.9
Auxiliary 2.1	17	180	10.6
Auxiliary 2.2	12	54	4.5

Fifteen blueback herring averaged 30.5 minutes each behind the north wingwall while two turbines were discharging and 13 herring averaged 145.2 minutes each behind the north wingwall while three turbines were discharging. Ten blueback herring averaged 54.9 minutes each behind the south wingwall when two turbines were discharging; 14 blueback herring averaged 126.7 minutes each behind the south wingwall with three turbines discharging.

Discussion

Blueback herring and American shad passage increased throughout the turbine study when powerhouse discharge decreased. Turbulence was noticeably reduced in front of the lock entrances when turbine 3 was shut down. Even though more fish were passed with two turbines off than with one turbine off, the difference was deemed insufficient to justify the increased cost of shutting down two turbines. Consequently, a flow agreement was reached with the SCPSA consisting of shutting down turbine 3 for a continuous 10 hour period prior to dusk each day during the fish passage season. Since this agreement, the average number of blueback herring passed increased from 189,689 (SD = 60,027) for 1988-1989 to 353,164 (SD = 262,164) for 1990-1992. Average American shad passage increased from 18,497 (SD = 11,944) to 134,730 (SD = 48,510) following the agreement. Negotiations are currently underway to extend the time turbine 3 is shut down during the fish passage season.

While the number of fish passed increased following the restrictions on turbine 3, the telemetry study suggested that blueback herring were still having difficulty in locating the lock entrances. Given the assumption that each of the 1601 fixes recorded from the tailrace area represented an attempt to move upstream of the dam, then each blueback herring averaged 61 attempts at trying to move upstream. Only 3.4% of the total upstream attempts were recorded in close proximity to the lock entrances and only one tagged fish was passed through the fish lock. Lock efficiency was therefore estimated at 3.0%. Comparison of blueback herring passage from 1986-1990 with a population estimate conducted on blueback herring during the same time period (Cooke 1990) indicated that only 2.1% of the population passed through the fish lock.

Tagged blueback herring remained longer (16.8 min/fish) near the fish lock entrances when turbine 3 was not discharging. Even with this increased time near the fish lock entrances, blueback herring were still unable to locate them or had no strong desire to enter and be passed upstream.

Blueback herring seemed to seek refuge from turbine-generated turbulence in the areas behind the wingwalls. Blueback herring spent 4.8 and 2.3 times more time behind the north and south wingwalls when the discharge was from three turbines rather than two turbines.

These results are consistent with telemetry findings at the Holyoke Dam in which American shad were repelled from the fish lift entrance due to extreme turbine discharge turbulence (Barry and Kynard 1986). Competition from adjacent turbine flow at the Conowingo Dam fish lift on the Susquehanna River also reduced the effectiveness of the fish lift entrance (RMC Environmental Services 1991).

In 1991, money was appropriated for the United States Army Corps of Engineers to study and correct the entrance problems at the St. Stephen fish lock. A 1:25 scale physical model of the dam and fish lock was built by the Corps Waterways Experiment Station in Vicksburg, Mississippi, to test various entrance designs. The final design modifications included two new fish lock entrances approximately 27 and 42 m downstream from the present entrances beyond the influence of the turbine boils. Barriers will exclude fish from congregating behind the wingwalls and guide them towards the new entrances. An alternate water source flowing around the dam from the forebay will increase the attraction flow up to 14 m^3/s while allowing juveniles and spent adult fish to emigrate. The modifications are scheduled to be completed by the spring of 1996 and will allow the fish lock to operate more efficiently during full generation.

TABLE 2.— Summary of radio-tagged blueback herring locations, with respect to the discharge of turbine 3, in the tailrace of the St. Stephen Dam and fish lock.

Location	Number of fish	Total time (min)	Mean time per fish	Fixes	Fixes per fish	Turbine 3
Aux 1.1	10	549	54.9	50	5.0	off
Aux 1.1	14	1,774	126.9	141	10.0	on
Aux 2.1	15	458	30.5	50	9.2	off
Aux 2.1	13	1,888	145.2	130	14.5	on
Aux 2.2	9	230	25.5	36	6.4	off
Aux 2.2	7	61	8.7	18	3.4	on

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Effects of a River Rediversion on Fish Passage and Blueback Herring Landings in Two South Carolina Rivers

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Abstract.—In 1985, approximately 71% of the Cooper River mean annual flow (442 m^3/s) was rediverted to the Santee River. The number of annual fish passed and blueback herring *Alosa aestivalis* landings were compared from a 5-year period before the rediversion to a 5-year period after the rediversion. The mean index of annual fish passage declined 80% and the mean annual landings of blueback herring declined 77% on the Cooper River after rediversion. Offsetting increases in fish passage and blueback herring landings were expected on the Santee River. However, the new fish lock constructed on the Santee River was not efficient at passing fish and did not mitigate the decline in fish passage on the Cooper River. Landings also declined on the Santee River due to changes in blueback herring migration patterns and restrictions on fishing access.

In 1938, the South Carolina Public Service Authority (SCPSA) initiated the Santee-Cooper Diversion Project. Santee River, which prior to the diversion had the fourth largest discharge (525 m^3/s) on the east coast of the U.S., was impounded at river km 140 by the Wilson Dam (Kjerve 1976). This dam served primarily as a flood control structure and created a 40,500 hectare reservoir, Lake Marion (Figure 1). Wilson Dam discharged a continuous flow of 15 m^3/s with periodic flood releases as high as 4,390 m^3/s. Mean annual discharge for the Santee River after the project was 62 m^3/s (Kjerve 1976). The remainder of the water exiting Lake Marion was diverted through a canal to another new reservoir, Lake Moultrie (27,000 hectares). This reservoir was created by impounding the headwaters of the Cooper River with Pinopolis Dam (river km 77). The Cooper River annual mean discharge increased from 2 m^3/s to 442 m^3/s (Kjerve 1976).

In addition to flood control, another objective of the Santee-Cooper Diversion Project was to utilize water from the Santee River drainage for hydroelectric power generation. The elevation difference between Lake Marion and Santee River at Wilson Dam was 6 m, while the head difference between Lake Moultrie and the Cooper River was approximately 23 m. By diverting water from the Santee River to Cooper River, greater hydroelectric power per unit flow was produced.

A fishery developed that took advantage of blueback herring *Alosa aestivalis* concentrations in the tailrace areas of Pinopolis Dam and Wilson Dam during the spring spawning runs. No facilities were provided for fish passage on the Santee River, however, a navigation lock at Pinopolis Dam provided incidental passage of migratory fish from the Cooper River into the lake system. Stevens (1957) documented that blueback herring, passed into the lakes by periodic boat lockings, provided up to 25% of the diet of adult striped bass *Morone saxatilis* in lakes Marion and Moultrie. Since then, SCPSA has operated the navigation lock to allow fish passage during the spring spawning migrations. This action not only supplemented the lake system's forage base but also provided anadromous fish access to spawning areas in the lakes and rivers above the dams.

A problem occurred as a result of the Santee-Cooper Diversion Project. Increased flows in the Cooper River accelerated shoaling in Charleston Harbor (USACE 1975). The cost of dredging navigation channels and the limitation of suitable disposal sites made harbor maintenance increasingly difficult. As a result, the Santee-Cooper Rediversion Project was proposed to limit the flow to Charleston Harbor. The project's operational guidelines restricted the Cooper River discharge to a maximum weekly average of 127 m^3/s. The remainder of the water was rediverted to the Santee River via a new canal (Figure 1). Rediverted water passed through the St. Stephen Dam which was constructed on the Rediversion Canal to maintain hydroelectric power generation capacity. In 1985, construction was completed and the discharge restriction on the Cooper River took effect.

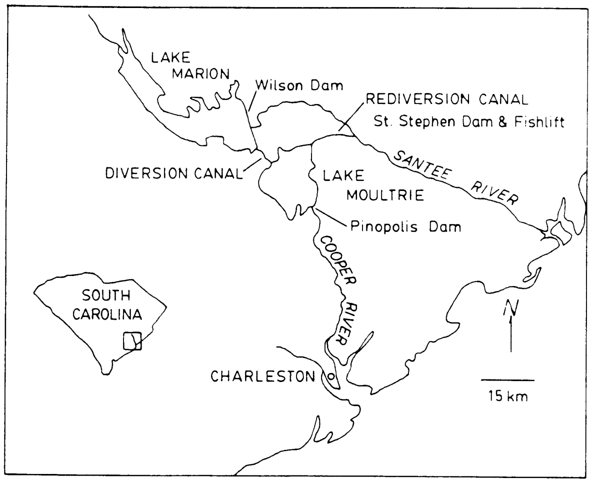

FIGURE 1.—Map of the Santee-Cooper system, South Carolina, illustrating major features of the Santee Cooper Rediversion Project.

During the planning stage of the Santee-Cooper Rediversion Project, concern was expressed that reduced discharge in the Cooper River would attract fewer blueback herring and result in reduced commercial landings and fish passage. Fisheries resources were predicted to decline in the Cooper River but increase in the Santee River (USACE 1975). In an effort to maintain the number of anadromous fish entering the lakes, a fish lock was constructed at the St. Stephen Dam. Assurances were given in the project's final environmental statement that if total anadromous fish passage declined, discharges to the Cooper River would be increased during the spawning runs (USACE 1975).

The objective of this paper is to present the results of a 10-year study documenting the effects of the rediversion on fish passage and blueback herring landings in the Santee and Cooper rivers. The results of decreased discharge on the fish passage and blueback herring landings in the Cooper River are given along with the results of increased discharge on herring landings in the Santee River. Although varying counting techniques precluded exact determination of the net effects on total fish passage in both rivers, data were collected that gave indications of the effectiveness of the mitigation measures.

Methods

Data for five years before rediversion (1980-1984) were compared to five years of data after rediversion (1986-1990). The 1985 season was omitted because the rediversion and the altering of water discharges went into effect midway through that year's spawning runs. Daily discharge data for the Cooper and Santee rivers were provided by SCPSA.

Cooper River

The single-lift navigation lock at Pinopolis Dam was approximately 18 m X 55 m with a vertical lift of 23 m. For fish passage, the downstream gates remained open for one hour before the lock was filled with water. Once the lock was full, the lakeside gates were partially opened to guide the exiting fish over an array of 11 transducers. The range on the transducers was staggered to compensate for overlap in the 9° hydroacoustic beams.

A Bendix hydroacoustic counter operating at 235 kHz was manually activated for a 5-min period after the gates were opened. The system recorded total biomass by integrating the fish echoes. Since preliminary studies indicated that blueback herring composed 97% of the fish being counted, the counter was designed to electronically divide the total biomass by the average biomass of an adult blueback herring (Curtis 1977). These values were used as an index of annual fish passage. The hydroacoustic operation is further described in Menin (1974) and Curtis (1977). Fish locking operations generally occurred three times each day from March 1 through approximately April 15. Fish locking was terminated when outmigrating fish interfered with counts. Analysis of variance ($\alpha \leq 0.05$; SAS 1985) was used to determine if a significant difference existed between the index of annual fish passage before (1980-1984) and after (1986-1990) rediversion.

Fishing for blueback herring in the Cooper River was restricted to March 1 - April 30. Fishing effort was directed at concentrations of fish below the Pinopolis Dam. Individual fishermen utilized circular hoop nets and cast nets to capture herring while drifting the tailrace in boats. Landings were monitored at available boat ramps seven days a week during the commercial season. Clerks interviewed all fishing parties at the completion of their fishing trip. The date, catch, and number of fishermen were recorded for each boat. Since regulations require dead blueback herring to be boxed, the catch of each fishing party was estimated by multiplying the number of boxes by 22.7 kg (average weight of a box of herring). Number of live herring harvested was estimated to the nearest dozen. Live catch data were later converted to kilograms by multiplying the number of estimated dozens by 2.2 kg, the average weight of one dozen herring. The catch per effort index (CPE) was calculated by dividing the season total herring catch by the total number of fishermen. Analysis of variance was used to test for significant differences in the annual landings and CPE before (1980-1984) and after (1986-1990) the rediversion.

Santee River

The fish lock was located at the St. Stephen Dam on the Rediversion Canal approximately 91 km from the mouth of the Santee River. Migratory fish were attracted into the entrance of the fish lock by an adjustable attractant flow. Once in the entrance channel, a crowder gate moved fish into the lock chamber. The lock chamber filled with water and a metal brail prompted the fish to swim up through the water column, a distance of approximately 15 m. When the fish reached the top of the lock chamber, they were released at lake level into the exit channel. The fish passed viewing windows before exiting into the canal and lake system.

A Bendix hydroacoustic unit was installed in the exit channel in 1986. Unlike the hydroacoustic unit at the Pinopolis Dam navigation lock, the transducers were located in an area of flowing water. Problems with high turbulence, entrained air and debris reduced reliability of these counts; therefore, the counts for 1986-1988 were not included in the results. Starting in 1989, all fish were visually counted and identified by species as they passed the viewing windows. Blueback herring were counted independently by one to three persons depending on fish density. Individual counts were then averaged at the end of each lift.

Landings of blueback herring were recorded from the tailrace below Wilson Dam. Groups of fishermen utilized seine nets approximately 23 m long to capture herring below the tailrace of Wilson Dam. Individual CPE data were not determined because varying numbers of fishermen participated in working the seines. Fishermen stopped using the tailrace of Wilson Dam after 1986 because of low catches. In 1990, a portion of the Rediversion Canal was opened to fishermen using hoop and cast nets. Creel censuses were conducted at available boat ramps at both sites using the same methodology as described for the Cooper River.

Results

Cooper River

Hydroelectric discharges from Pinopolis Dam during the anadromous fish spawning season (February through April) declined from an average of 552 m^3/s with a mean generating schedule of 24 h per day before rediversion (1980-1984) to 130 m^3/s with an average of 13 h of generation per day after rediversion (1986-1990; Table 1). The average index of annual fish passage at the Pinopolis Lock during the 5-year period prior to rediversion (mean = 5,732,187; SD = 3,702,250) was significantly (P = 0.0305) higher than the 5-year annual average after rediversion (mean = 1,174,257; SD = 1,178,775; Table 2). After rediversion the index of annual fish passage declined progressively in each successive year.

Blueback herring landings on the Cooper River averaged 171,263 kg/year (SD = 87,814) from 1980 to 1984 compared to 37,957 kg/year (SD = 26,545) from 1986 to 1990. Average annual CPE was reduced from 127 kg/d before rediversion to 47 kg/d after rediversion. Analysis of variance indicated significant differences in average annual landings (P = 0.0117) and CPE (P = 0.0006) between time periods.

Santee River

Counts of total fish passage were available only for 1989 and 1990 at the fish lock (Table 2). The average number of total fish passed was 176,300/year (SD = 19,799) for these years. The average discharge during this period was 448 m^3/s (SD = 81) with an average generating time of 19.5 hours per day (SD = 5; Table 1).

Commercial herring fishing at Wilson Dam was limited to two of the five study years before rediversion because of high water and prohibitive fishing regulations (Table 2). Commercial harvests at Wilson Dam averaged 71,386 kg/year (SD = 55,842) for 1980 and 1981. The 1980 season was limited to only 5 days of successful fishing due to flood spillage. Landings at Wilson Dam decreased to 35,200 kg in 1986 and were negligible in 1987-1990. In 1990, the Rediversion Canal was opened temporarily and yielded 1,154 kg (CPE = 13 kg/d).

Discussion

The Santee Cooper Rediversion Project reduced the Cooper River's mean annual discharge by 71% and discharge during the anadromous fish spawning season from February through April by 76%. In addition to the reduction in the volume of discharge, hydroelectric generation switched from a continuous mode of operation to a peaking mode which included substantial periods of no discharge (Table 1). Blueback herring landings declined by 77% and the index of annual fish passage declined by 80% after these flow changes. These observed declines may be due to a number of factors associated with rediversion. For example, fewer blueback herring may have been attracted into the river by the reduced discharges. Alabaster (1970) observed a greater number of salmonids in traps during periods of increased flow suggesting that a higher number of fish entered the river. Blueback herring and alewife *Alosa pseudoharengus* preferred experimentally modified channels with higher velocities than channels with lower velocities (Collins 1952). Also, blueback herring may have moved downstream of the tailrace area during the periods of zero discharge that occurred after rediversion where they would not be available to passage and capture. Radio-tagged chinook salmon *Oncorhynchus tshawytscha* moved downstream from the Little Goose Dam on the Snake River after spillage ceased (Haynes and Gray 1980).

Mark-recapture experiments (Cooke 1990) indicated that the 5-year annual average of number of blueback herring using the Santee River from 1980-1984 increased from 3,118,226 (SD = 1,964,990) to 6,648,306 (SD = 2,444,323) in 1986-1990, following rediversion. To determine if these blueback herring were entering the new Rediversion Canal or continuing up the Santee River, gillnets were simultaneously fished on 18 days at both locations approximately 1.5 km upstream of their junction (Christie and Cooke 1987). Average catch per minute for blueback herring was 0.83 (SD = 0.62) in the Rediversion Canal and 0.19 (SD = 0.19) in the Santee River. Large numbers of blueback herring were observed in the Rediversion Canal but relatively few were being passed. Peaking operations at the St. Stephen Dam, along with siting problems of the lift entrance, may have contributed to the failure of the fish lock to capitalize on the blueback herring available in the Santee River. During periods of zero discharge blueback herring did not concentrate below the dam and few were attracted into the fish lock. Blueback herring would concentrate below the dam during periods of discharge, but fish could not locate the entrance to the fish lock due to high turbulence (Chappelear and Cooke 1994). Similar findings were documented at the Holyoke Dam fish lift where American shad had problems locating fishway entrances among turbulent discharges (Barry and Kynard 1986). The results of the fish passage data collected during the study were used to justify a request to have the Cooper River water flows increased during the anadromous fish spawning season. This request was denied based on the increased dredging cost associated with increased flows in the Cooper River. However, funding was secured to modify the lift and interim flow restric-

TABLE 1.— Average daily discharge (m^3/s) and generation time (h/d) for the months of February through April for the Cooper River and Santee River, South Carolina. Standard deviations are given in parentheses. NA = not applicable.

	Pinopolis Dam		St. Stephen Dam		Wilson Dam	
Date	Discharge	Generation	Discharge	Generation	Discharge	Generation
1980	689 (185)	24 (0)	NA	NA	8,820 (14,950)	24 (0)
1981	202 (87)	24 (0)	NA	NA	515 (0)	24 (0)
1982	496 (145)	24 (0)	NA	NA	4,818 (5,683)	24 (0)
1983	783 (20)	24 (0)	NA	NA	11,083 (11,331)	24 (0)
1984	590 (6)	24 (0)	NA	NA	12,704 (9,200)	24 (0)
1985	337 (278)	17 (9)	11 (2)	1 (4)	515 (0)	24 (0)
1986	125 (74)	11 (5)	91 (144)	4 (7)	515 (0)	24 (0)
1987	131 (91)	10 (6)	607 (149)	22 (4)	4,706 (14,581)	24 (0)
1988	127 (61)	11 (4)	97 (108)	7 (6)	515 (0)	24 (0)
1989	128 (69)	11 (4)	391 (274)	16 (10)	515 (0)	24 (0)
1990	137 (65)	20 (6)	506 (147)	23 (4)	3,507 (4,881)	24 (0)

TABLE 2.— Annual indexes of total fish passage and blueback herring landings (kg) for the Santee River and the Cooper River, South Carolina. Average landing per fishermen trip is given where available (CPE). * = estimates not available. NA = not applicable.

	Cooper River		Santee River	
Year	Fish Passage	Blueback herring landings (CPE)	Fish Passage	Blueback herring landings (CPE)
1980	8,620,882	177,441 (137)	NA	31,900
1981	3,485,008	71,391 (94)	NA	110,872
1982	3,145,460	93,426 (142)	NA	Flood release
1983	2,652,067	262,614 (117)	NA	Prohibited
1984	10,757,517	251,445 (146)	NA	Prohibited
1985	Rediversion went into effect at mid-season			
1986	3,010,200	66,028 (90)	*	35,200
1987	1,703,040	67,987 (49)	*	Flood release
1988	527,969	20,132 (39)	*	0
1989	397,131	17,791 (30)	190,300	0
1990	232,764	17,846 (27)	162,300	1,154 (13)

tions at the dam have been granted by the operating utility company (Chappelear and Cooke 1994).

Landings of blueback herring in the Santee River were expected to offset the losses in the Cooper River (USACE 1975). However, blueback herring appear to no longer be concentrating at Wilson Dam, the historic fishing site since the Santee River was impounded in the 1930's. The fishermen have consequently abandoned the Wilson Dam site. After rediversion, the majority of blueback herring entering the Santee River were migrating up the Rediversion Canal (Christie and Cooke 1987) which was closed to boat traffic and commercial fishing. In 1990, a portion of the Rediversion Canal was temporarily opened to determine if blueback herring could be successfully harvested (Table 2). Based on data from this study the Rediversion Canal was opened to bait fishermen. Landings for 1991 and 1992 were 8,859 kg and 82,673 kg. These landings represent an increase over the 1986-1990 landings after rediversion but are still well below the average Cooper River landings (171,263 kg) from before the rediversion.

Data show that fish passage and commercial herring landings in the Cooper River were reduced approximately 80%, while population numbers increased in the Santee River. Blueback herring previously entering Cooper River may have been attracted to Santee River in response to flow changes. Blueback herring are reported to home to their natal rivers (Messiah 1977; Cooke 1987; Loesch 1987). Stream selection is thought to be based on olfactory cues (Thunberg 1971) or responses to other abiotic factors of the stream such as water temperature or velocity (Collins 1952). It is unclear whether the blueback herring shifted from the Cooper River to the Santee River in response to the higher discharges, because the same water (and olfactory cues) that may have previously guided fish in the Cooper River is now being discharged in the Santee River. A better understanding of the orientation factors affecting migrations will improve our ability to manage and conserve blueback herring and other migratory fish.

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Fish Passage Facilities For *Alosa*

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Abstract.—Dams and other instream barriers have prevented many anadromous species from ascending coastal streams to spawn in their historical habitat. The construction of many types of fishways and lifts around these barriers has succeeded in restoring some migratory populations. Four major fishway types are used in large rivers: Denil; pool; pool and weir; and lift. The Denil fishway is the most common type in the Northeast United States and will pass *Alosa* but not striped bass *Morone saxatilis* or sturgeon *Acipenser* spp. The most common pool fishway is the vertical slot. This high-volume fishway is effective in passing *Alosa* but not striped bass or sturgeon. Several pool fishways are under construction in the Lehigh River, Pennsylvania. The pool and weir fishway is dependent upon maintaining a constant depth and flow volume and may require more mechanization than either the pool fishway or the Denil. It is capable of passing large numbers of fish. The fish lift can be constructed in a limited space at relatively low cost but maintenance and operation costs are high. Two fish lifts operate at the Conowingo Dam, Susquehanna River, Pennsylvania, and another operates at the Emporia Dam, Meherrin River, Virginia. Other types of fish passage facilities are navigation locks (Lake Moultrie, South Carolina) and notches in low-head dams, culverts, stream regulation weirs, and gaging stations. These are more common in southeastern streams.

The presence of dams without adequate upstream fish passage facilities along river systems has prevented or significantly reduced the numbers of migratory fish that return to the available habitat. The *Alosa* do not share the same leaping ability or swimming characteristics as the salmonids and are more dependant upon adequate upstream fish passage facilities for being able to pass barriers to reach their spawning areas. Downstream fish passage facilities are also essential so that the spawned-out adults, as well as their fry, can safely pass over the same barriers on their journey back to the sea. There are several general categories of upstream fish passage facilities which, if designed and constructed properly, will pass a very large percentage of those fish that have a desire to ascend upstream. These various types of upstream passage facilities are:

Chute Type Fishways
- Denil Fishways (includes steeppass)

Pool Type Fishways
- Vertical Slot Fishways
- Pool and Weir Fishways
- Ice Harbor Fishways

Mechanical Devices
- Fish Lifts (Elevators) or Fish Locks
- Navigation Locks

Breaches
- Notches & Partial or Complete Breaches

It is imperative that adequate background information be available to the fishway designer. Successful fish passage design is a team effort involving fisheries biologists and engineers. All have a role to play in the process. River management plans should be developed for the target species, and its estimated design population and migration period must be known. This allows the staff to determine the stream flow ranges during the migration periods and to set the engineering and hydraulic design parameters for the proposed passage facility. If the target species are not present, or are present in low numbers, an upstream seeding program may be undertaken to enhance restoration. Another critical item is having a good field survey of the area so that accurate dimensions and elevations of the dam and its surrounding area are known. Lastly, properly located staff gages along with readings during high and low flow conditions are necessary to establish the invert elevations of the entrance and exit channels during the migration period. All this information should be available prior to the initiation of any design work on the fishway.

Chute type fishways

Denil fishway. The Denil fishway is the most common fishway in the Northeast and is reliable. Because of its small size it is the least costly of the four major types of fishways. Typical design features are shown in Figure 1. It will pass most migratory species and all *Alosa*. Of all the migratory species, only spawning-sized striped bass *Morone saxatilis* and sturgeon *Acipenser* spp. are reluctant to negotiate a Denil fishway. Under normal conditions a 4 ft wide Denil fishway can safely accommodate about 25,000 adult American shad *Alosa sapidissima* in a migration season. If American shad is a target species, the recommended floor slope of the Denil is 1 ft rise for every 8 ft of run, and the width of the fishway is generally 4 ft. If river herring is the target species, a 3 ft wide, 1 on 6 sloped Denil fishway is normally used. Baffles are set at a 45° angle to the floor, sloping upstream. For a 4 ft wide fishway, the actual clear opening in the baffle is 28 in. Fish must swim continually in the sloped Denil baffle section of the fishway and can rest at the pools either upstream or downstream of the baffle sections. The typical criteria allows no more than 6 to 9 ft of vertical rise before requiring a resting pool.

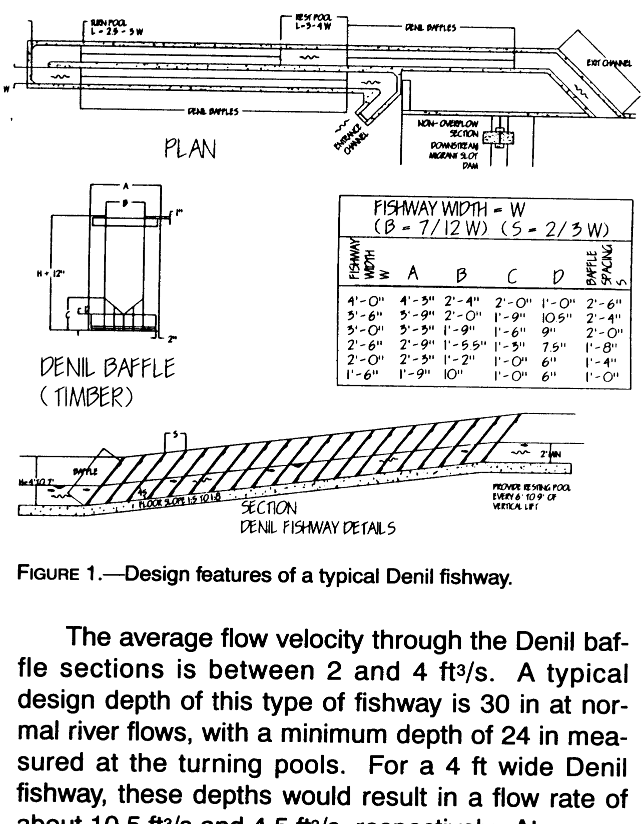

FIGURE 1.—Design features of a typical Denil fishway.

The average flow velocity through the Denil baffle sections is between 2 and 4 ft^3/s. A typical design depth of this type of fishway is 30 in at normal river flows, with a minimum depth of 24 in measured at the turning pools. For a 4 ft wide Denil fishway, these depths would result in a flow rate of about 10.5 ft^3/s and 4.5 ft^3/s, respectively. At a maximum design depth of 4 ft, the 4 ft wide Denil can pass about 37 ft^3/s. The entrance of the fishway, as is the case for virtually all of the six types of fishways, is located close to the base of the dam and along the side of the dam that lies the farthest upstream.

Maintenance considerations are relatively minor for a Denil. The fishway should be inspected at least twice a week during the migration period to remove debris wedged inside the baffles, and to clean off the trash rack or trash boom at the exit channel. Additionally, some minor adjustments to the stoplogs in the fishway entrance channel may be required. The wooden baffles have to be replaced about every 8 to 10 years depending upon fishway location and what type of wood is used in the construction. The typical construction cost for a Denil is \$12 - 15,000 per vertical foot of rise. Costs increase if either additional attraction water or an additional entrance is necessary. Design and construction administration costs run about 25 percent of the construction costs.

Denil fishways have been built with lifts up to 50 ft on the St. Croix River in Maine where the target fish is primarily Atlantic salmon. A Denil fishway with a vertical lift of 29 ft has recently been built on the Maurice River at Union Lake, New Jersey, which was designed to pass American shad. It is reported to work well in passing both shad and river herring. At least seven Denil fishways have been constructed in the Chesapeake Bay drainage area in the last several years and over 75 have been constructed in New England since 1965.

Another type of a Denil fishway is the "Alaska steeppass." This is a prefabricated aluminum fishway that can be assembled in the field rather easily. Several sections can be joined together. They are typically available in 10 ft sections. The most common, the Model "A", has an overall width of 22 in and a height of 27 in. The clear distance between the aluminum vanes is 14 in and they are set at 10 in on center. The deepened steeppass is almost identical, except that the height is 49 in, thereby allowing up to a doubling of the flow. More energy is dissipated in this type of fishway because the baffle spacing is closer, thereby allowing the fishway to be set at a steeper slope than a typical Denil. However, due to the clear opening being only 14 in, this type of fishway is much more prone to becoming clogged with debris. A major limitation to this type of fishway is that due to the very limited height of the Model "A", the fishway can only be used in river systems having very limited fluctuation in both headpool and tailwater levels, and can pass only small volumes of flow. The cost differential in using the prefabricated steeppass over the conventional Denil model is generally minimal, if turning pools and entrance and exit channels are required, or if a deepened steeppass is necessary. A section of Model "A" costs approximately \$5,000 FOB, Boothbay Harbor, Maine. Several steeppasses have been constructed for river herring on small coastal streams in New Jersey, and several are in the advanced design stage in Maryland.

Pool Type Fishways

Vertical slot fishway. The most common pool type of fishway is the vertical slot (Figure 2). These are high volume fishways capable of passing large numbers of fish. They are usually located on major rivers such as the Connecticut or Lehigh. The pools are sized to accommodate the design population of fish. Each pool is, in effect, a resting pool, and the upstream migrating fish may spend up to 3 to 5 min in each pool. The minimum depth of water in a pool is 4 ft with the average depth being 6 ft. A normal pool is 10 ft long. This type of fishway cannot pass spawning-sized striped bass or sturgeon. If the target species is American shad, the drop per pool should be no more than 9 in and the width of the vertical slot opening should be 16 to 18 in. Some early vertical slot fishway designs for American shad in New England had slot openings of only 10 in. Because of their milling and fallback behavior, poor-swimming shad would come in contact with the sides of the slots, resulting in significant descaling and subsequent mortality. The reports based upon the failures at these projects therefore incorrectly stated that vertical slot fishways in general could not safely pass American shad.

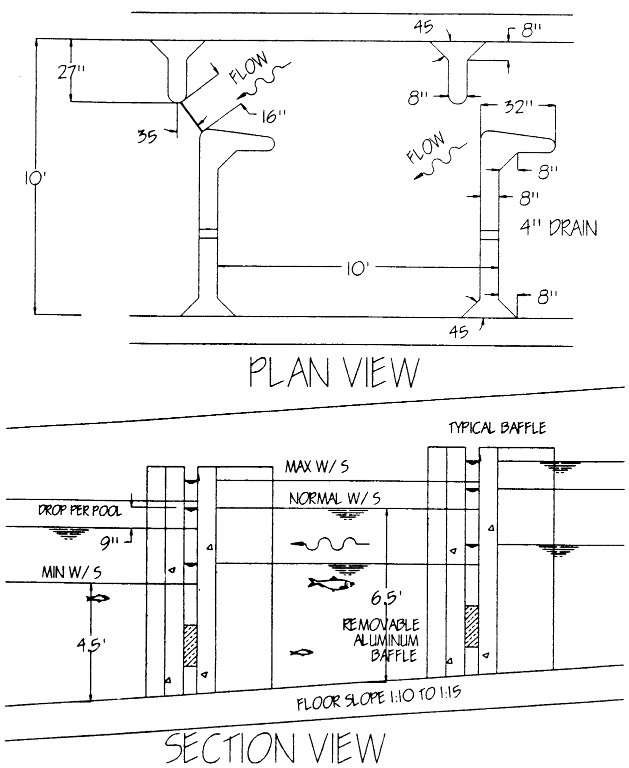

FIGURE 2.—Plan and section views of a typical vertical slot fishway.

Aluminum baffle plates are normally inserted in the slot opening about 12 in above the floor to allow for the creation of an orifice and to reduce the volume of flow and pool turbulence. Salmonids prefer to pass through the orifice whereas American shad are reluctant to pass through an orifice, preferring to swim over or through the slot. For this reason, it is imperative that no horizontal member of a fish passage facility be in the water column that could result in the creation of an orifice flow condition. At an average depth of 6 ft with a baffle plate of 2 ft inserted in the slot, a 16 in wide vertical slot will pass about 35 ft^3/s.

The "beauty" of a vertical slot fishway is that it is self regulating, i.e. mechanical gates, stoplogs, or baffles need not be mechanically raised or lowered to account for varying flow conditions. Rather, as the headpool rises, flow depths increase uniformly throughout the fishway, and the fishway does not become drowned out or have excessive depths of flows coming downstream through the fishway. Fishways of this type usually are required to remain operational through a wide variation in flow levels. Since these fishways can be built on large river systems and generally at hydro projects, additional attraction water is required to be introduced in the fishway entrance channel. This flow usually comes from the headpool and requires an energy dissipation chamber. Service design criteria require that up to 3% of the turbine capacity be provided as attraction flow, discharged through the entrance channel of the fishway. This usually requires that the entrance channel pool be sized to accommodate the additional attraction water coming out of the floor diffusor. The maximum allowable velocity exiting the floor diffusor is typically less than 1 ft/s. Flow exiting the fishway entrance channel can be controlled by a mechanized weir gate that is controlled by the hydroplant's tailwater level sensor.

All of these additional design parameters result in a significant increase in costs. An average vertical slot fishway costs up to $50,000 per vertical foot of rise for construction costs alone! Maintenance costs are moderate and minimal staffing requirements are necessary in comparison to the other main stem type of fishways. Items requiring inspection and cleaning are the attraction water system, especially the diffusor screen in the entrance channel, trash racks or trash boom, observation windows, and picketed leads.

There are no existing vertical slot fishways in the Chesapeake Bay area. Several are being constructed on the Lehigh River in Pennsylvania, and a third is already in place. A vertical slot fishway is currently under design for Boshers Dam on the

James River in Richmond, Virginia, and a possibility exists for constructing a vertical slot fishway at Embry Dam on the Rappahannock River after a final determination is made by the city of Fredericksburg on the resolution of water supply issues.

Pool and weir fishways. As with vertical slot fishways these are primarily considered to be main stem, high volume fishways capable of passing large runs of fish. Many of the design parameters are the same as for the vertical slot fishway. Each of the pools in this type of fishway is considered to be a resting pool (Figure 3). These fishways are very dependant upon maintaining a constant depth and volume of flow passing downstream through the fishway. This type of a fishway requires that orifices be placed at the base of the baffles. Mechanical gates at the top weirs just before the exit channel are required to keep the depth of flow constant. Some of the facilities in New England require seven mechanized gates to accommodate the normal variation in flow levels.

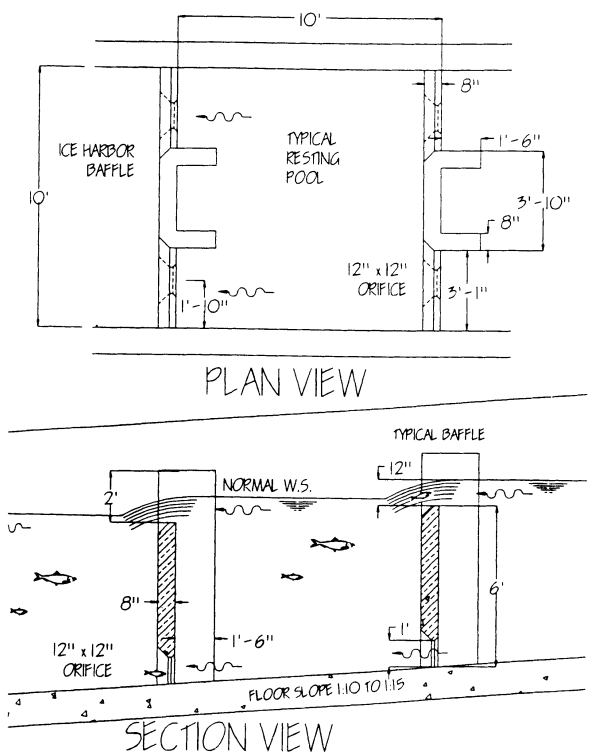

FIGURE 3.—Plan and section views of a typical pool and weir fishway.

A "streaming or shooting" flow regime is used if the target species is American shad. This requires that about 14 in or more of flow passes over each weir. The surface of the water between the weirs is turbulent. If the target species is salmonids, a different flow regime can be used, called "plunging" flow. This flow pattern appears to be much less turbulent, with fairly slack water downstream of the weir and a backroll at the surface. Just above the next downstream weir in the same pool, the water bubbles to the surface. This type of flow regime is achieved by passing 12 in or less of flow over each weir. Obviously, the difference in flow depths between plunging and streaming flow conditions is very small, but very important for the primary species being passed. Virtually all design parameters described above under vertical slot is applicable to pool and weir fishways.

Ice Harbor fishway. This is a specialized type of a pool and weir fishway. The information described above is all pertinent to the Ice Harbor fishway. The terminology "Ice Harbor" designates the special baffle configuration and denotes the location where the original design was utilized - the US Army Corps of Engineers Ice Harbor Dam on the Snake River in Washington.

In all likelihood, very limited use will be made in the future for the Ice Harbor fishway and other pool and weir fishways. They are far more complex than a vertical slot fishway, both mechanically and operationally, requiring constant inspection of pool levels. A properly designed pool and weir fishway costs about the same as a vertical slot. The Ice Harbor fishway on the Connecticut River, Massachusetts, is the closest to Chesapeake Bay. This type of a pool and weir is much different in design considerations than the small pool and weirs described below.

Mechanical devices

Fish lifts (or fish elevators) and fish locks. This type of fish passage facility can be constructed either on tributary streams or on mainstem rivers. Fish lifts and fish locks are very similar in design incorporating identical features for all but the lifting mechanisms. A schematic view of a fish lift is shown in Figure 4, and the fish lock is shown in Figure 5. Fish lifts can be constructed in a very limited space and can be designed for high dams as well as low-head dams. The only real differences in the design of a 20 ft high fish lift and a 75 ft high dam is the length of the hoisting cables, the diffusion system, and the hopper superstructure. An additional feature of the fish lift is that it can accommodate trap and transport operations or a direct release into the headpool depending upon the fisheries management plan.

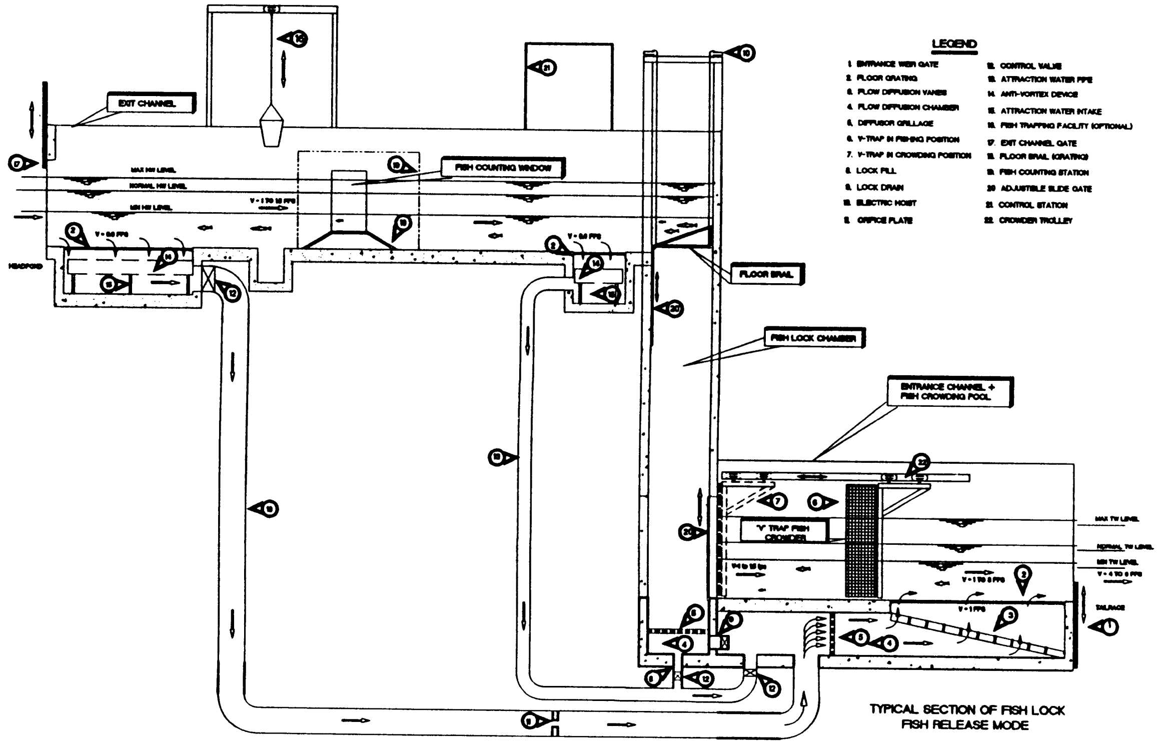

FIGURE 4.—Schematic of a typical fish lift. These structures are suitable for limited spaces.

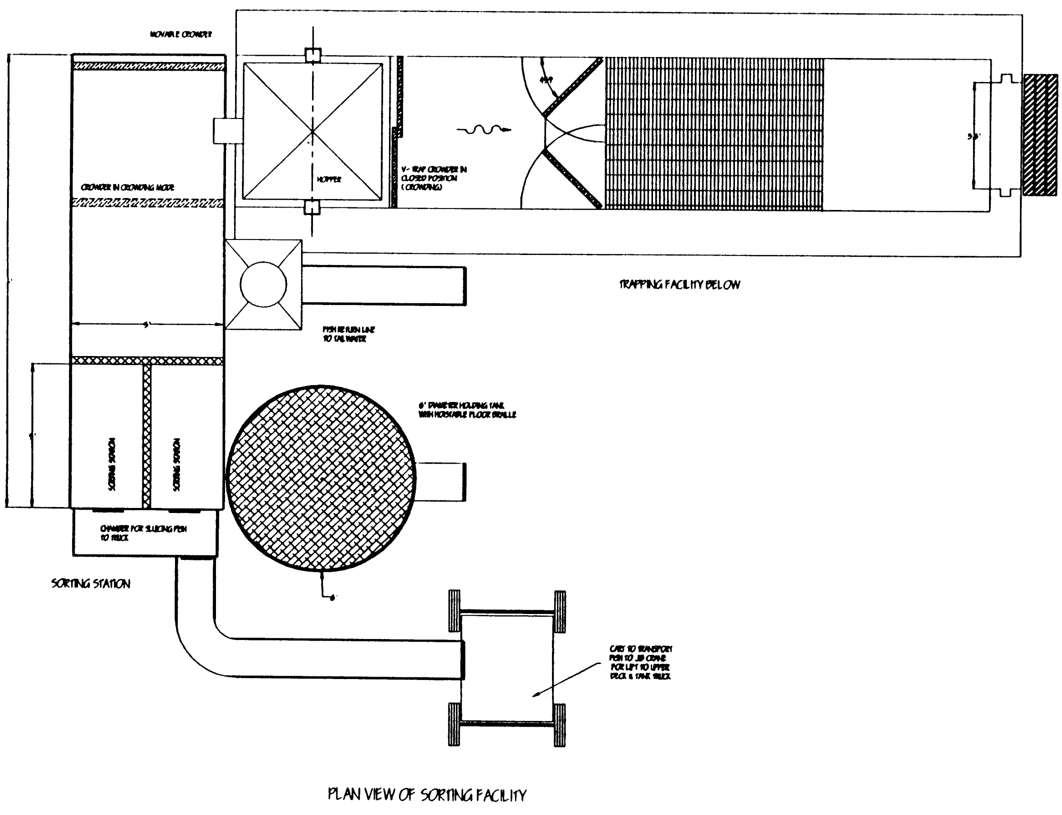

FIGURE 5.—Schematic of a typical fish lift with a fish lock at the downstream end of the lift.

The major parts of a fishlift are as follows: the entrance channel and floor diffusor; the fish trap crowder; the lifting or hoisting mechanisms; and the exit channel. Many of the fishways in this category (as well as the pool and weir fishways) also have a fish counting facility as an integral part of the exit channel. The fishway entrance and floor diffusor are similar in design considerations to either a vertical slot or pool and weir fishway. About 75% of the total flow is discharged through the floor diffusor, with the remaining 25% entering the fish lift or lock from just upstream of the hopper or the elevator shaft. One of the more common type of fish crowders is the V-trap crowder. It is usually located just upstream from the floor diffusor. It usually consists of two hinged gates (grating) or wings which, when in the fishing position, guide the fish into a narrow opening in the middle of the channel. Since there is flow coming into the fishway immediately upstream of the hopper or floor braille, fish pass through this narrow opening into the holding pool, usually over the hopper of the fish lift or the floor braille of the fish lock. A separation screen prevents the fish from moving past the hopper or floor braille. After an appropriate period of time, called the fishing cycle, the V-trap crowder is closed, and the crowder then moves upstream, called the crowding position, forcing all fish over the submerged hopper or floor braille. A second separation gate is then dropped in place by a hoist system if it is a fish lift, or, if it is a fish lock, a watertight mechanical gate is closed, sealing off the chamber. The V-trap crowder then returns to its normal "fishing" position.

The lifting mechanism in a fish lift is a hopper attached by cables to a hoisting mechanism. The hopper is essentially an enclosed bucket containing a small volume of water and the crowded or trapped fish. The hopper is then raised out of the water column of the tailrace by the cables and the hoisting system. The fish are then discharged into either an exit channel leading into the headpool or into sorting tanks if the facility is a trap-and-truck operation (Figure 6). If the facility is a fish lock, the chamber is flooded with water and the water levels in the exit channel and the elevator shaft reach equality. A hoistable floor braille is then raised by means of a

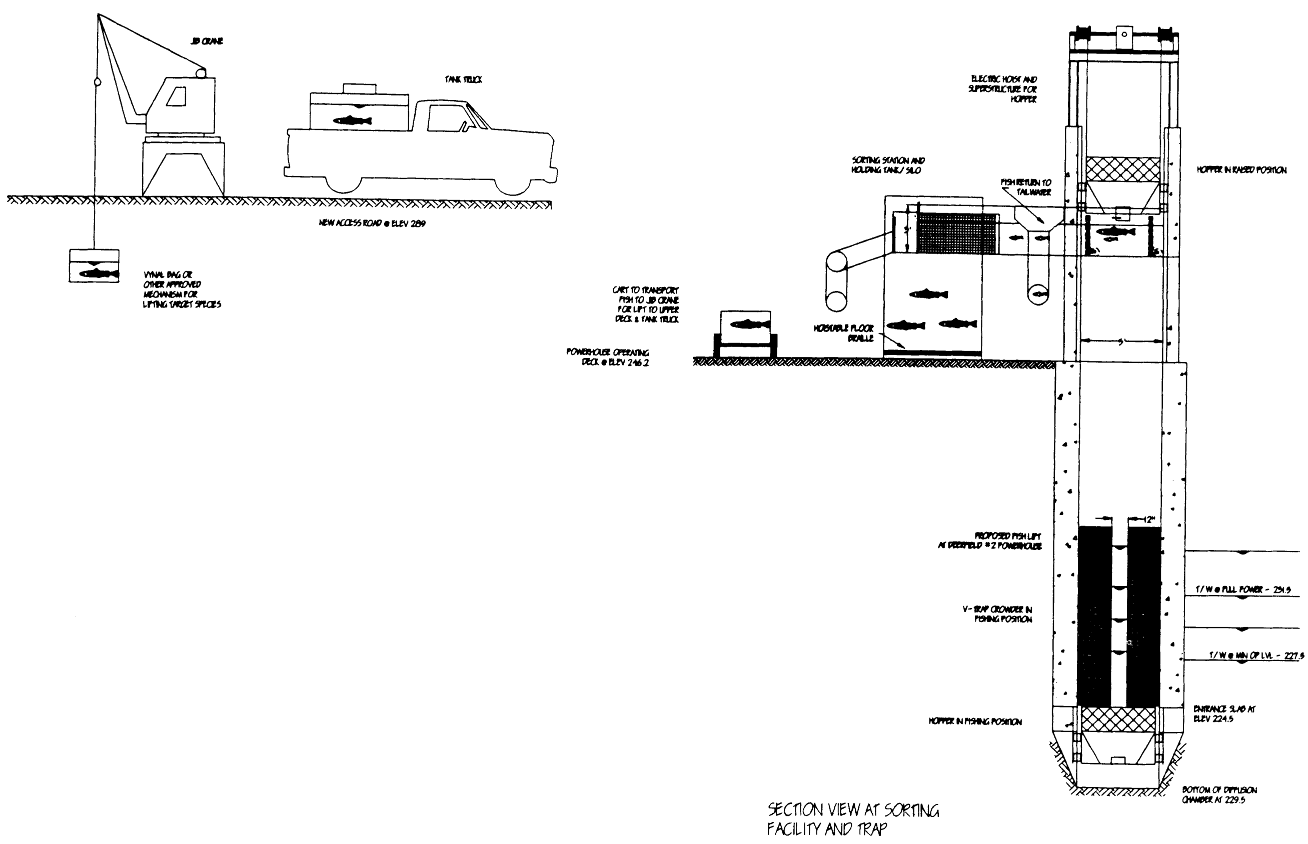

FIGURE 6.—Plan view of trapping and sorting facility for a typical fish lift and fish lock.

cable system attached to a mechanical hoist, forcing the fish to move up to the exit channel. A fish lock is supposedly less stressful on fish than a fish lift since in a lock, the fish are not as crowded as in a fish lift hopper. However, because of the additional construction costs and slower cycle times the usage of a lock over a lift is questionable. Under either type of lifting mechanisms, the hopper or the floor braille is then returned to the down position. Either the separation gate or the watertight mechanical gate is then raised so that the normal fishing mode can resume.

One of the advantages of a fish lift over the pool and weir or vertical slot fishway is that it can be built in a limited space and can have significantly lower construction costs. Another advantage of a lift is that it is amenable to staged construction (size of facility increases as fish runs increase) and the lift minimizes passage delays found in a fishway. However, the maintenance and operation costs are high, and because of the abundance of moving parts, an adequate parts inventory must be maintained. Another significant advantage of the fish lift is that it can be designed to pass spawning-sized striped bass and sturgeon, something none of the previously described fishways will do. Construction costs are extremely varied and cannot be accurately reported on a cost per vertical foot of rise.

There are two fish lifts currently in operation at Conowingo Dam on the Susquehanna River, and another at the Emporia Project on the Meherrin River in Virginia. The only lock system in operation along the Atlantic seaboard of the US is located at Lake Moultrie on the Santee-Cooper River system in South Carolina. A fish lift is currently under construction at the 45 ft Brasfield Dam on the Appomattox River in Virginia, and plans have recently been announced that fish lifts will be constructed on the next three upstream dams above Conowingo on the Susquehanna River in Pennsylvania. The technology presently exists for remote operation of a fish lift. More usage of this system will be likely even on small-sized projects that may normally require a Denil fishway.

Navigation locks. Another type of mechanical device that successfully passes virtually all types and sizes of fish is the navigation lock. Although designed to pass boat traffic, the navigation lock contains the necessary attraction water components that attract fish into the lock chamber along with the boat that will be lifted. Once the boat (and the fish) is inside the chamber, the downstream gates are closed. Water is then allowed to enter the sealed off lock chamber until the level inside the chamber and the headpool are the same. The upstream gates are then opened, and the boat, along with the fish, pass upstream. Navigation locks successfully pass *Alosa* on the Charles, Cooper, Merrimack, Savannah, Columbia, and Chickahominy rivers.

A summary of constructed fish passage projects in the Chesapeake Bay area is given in Table 1 and proposed fish passage projects is summarized in Table 2.

Breaches

Notches and partial or complete breaching of dams. This category is included as a separate item because of its potential use in the Bay area. The maximum difference in water levels cannot exceed 3 ft because of high velocities due to different water levels upstream and downstream of a notch. At that 3 ft head difference, the average velocity immediately below the notch can approach 14 ft/s. To be able to pass through this high velocity, *Alosa* must swim near their burst speed. When designing a notch the invert of the notch must be at or below the downstream pool level so that the clupeids can swim through. Many streams in the Bay area have barriers that can be made passable by simple notching. This is particularly true at some culverts, stream regulation weirs and US Geological Survey Gaging stations. The size of the notch is dependant upon drainage area. A notch is capable of passing many species and possibly spawning-sized striped bass. In some instances, minor downstream channel modifications may be necessary to increase the water surfaces immediately below the notch. A minimum 3 ft deep plunge pool is recommended immediately below the notch so that the energy from the fall can be dissipated.

There are several major river systems in the Bay area where notches have been installed or are being proposed. Notches have been placed in the Manchester and Browns Island Dams on the James River and another notch is maintained at the Harvell Project on the Appomattox River in Virginia. A 2.5 ft deep notch is proposed for the Williams Island project on the James River in Richmond, and a 2 ft deep notch is proposed for the Potomac River at Little Falls Dam. Both proposed notches would be about 30 ft long. Several US Geological Survey gaging stations in Maryland have had their control weirs notched, and the notch was increased on a stream regulating weir on the Anacostia River.

TABLE 1.— Summary of proposed upstream fish passage projects in the Chesapeake Bay area as of December, 1992, excluding culverts, minor notches, and channel improvement projects.

River	State	Name (H = Hydrodam)	Fishway type	Height (ft)	Slope	Width (ft)	Comments[a]
Patapsco	MD	Simpkins	Denil	17	1 on 8	4	In late stages of negotiations with MD DNR, DA=300 SM
Deer Creek	MD	Wilson Dam H	Denil	5	1 on 6	3	EPA funded, possible FERC action, awaiting conceptual plans, DA ≈ 150 SM
Andover Br. Chester	MD	Andover	Denil	8	1 on 6	3	EPA funded project, awaiting conceptual plans, DA = 43 SM
Susquehanna	PA	Holtwood H	Fish lift (2)	64		10 @SP 12 @PH	Pa. Power and Light will construct lifts at SP and PH, DA = 26794 SM
Susquehanna	PA	Safe Harbor H	Fish lift (2)	63		10 @SP 12 @PH	SHWPC will construct lifts at SP and PH DA = 26117 SM
Susquehanna	PA	York Haven H	Fish lift	23		12	YHP agreed to construct lift at powerhouse, DA = 24930 SM
Rock Creek	DC	Pierce Mill	Denil	6	1 on 6	3	Owned by NPS, other passage problems upstream and downstream, DA ≈ 65 SM
Potomac	VA, MD, DC	Little Falls	Notch	4.5	1 on 10 ramp	30	30 ft x 2 ft notch proposed, USCOE owned, private group donated funds to pay for surveys, USFWS will model, DA = 11560 SM
Rappahannock	VA	Embry	Vertical slot	20	1 on 12	8 X 10 pools	City owned, funding problem, possible removal of dam with new water intake upstream, DA = 1596 SM
Appomattox	VA	Harvell H	Fish lift or multi-denil	10	1 on 8	6 4	Awaiting construction, currently approved plans (Sect 18) call for lift, possible staged construction for 2 or more Denils, DA = 1340 SM
Appomattox	VA	Battersea H	Downstream passage notches	3		100	Awaiting construction Notches exist, DA = 1340 SM
Appomattox	VA	Brasfield H	Fish lift	41		6	Should be under construction shortly, approved plans, DA = 1335 SM
James	VA	Williams Island	Notch	3		30	30 ft x 2.5 ft notch, analysis of impacts on upstream water surfaces approved by city, awaiting structural analysis of dam, DA = 6758 SM
James	VA	Boshers	Vertical slot	11	1 on 12	10 X 15 pools	Awaiting final conceptual plans, funding by ?, Richmond has ojections to priority, phased construction with second fishway needed on right bank, DA ≈ 6750 SM
Mattaponix (tributary to Rappahannock)	VA	Mattaponix	Denil	17	1 on 6	3	Owned by sand and gravel company, may be willing to cost share, awaiting conceptual plans, DA ≈ 35 SM
York	VA	Ashland Mill	Denil	11	1 on 6	3	Awaiting conceptual plans, possible EPA funding, DA = 394 SM

[a] DA = drainage area; SM = square miles; SP = spillway; PH = powerhouse.

Small pools and weirs. This is a category of fishway designs that can work under a limited operating range, and this brief description is not intended as being all inclusive. It briefly describes small fish passage projects that have been successful in passing *Alosa*. These would not fully satisfy the operating and design conditions that US Fish and Wildlife Service normally uses, but given the right set of operating conditions, they can be built rather cheaply and can pass a limited number of fish.

The most notable type of fishway included in this category is the small pool and weir fishways formerly built by the Massachusetts Division of Marine Fisheries, particularly along south-shore coastal streams and on Cape Cod (they now build Denil fishways in most cases). Many of these fishways

TABLE 2.— Summary of constructed fish passage projects in the Chesapeake Bay area as of December, 1992, excluding culverts, minor notches, and channel improvement projects.

River	State	Name (H = Hydrodam)	Fishway type	Height (ft)	Slope	Width (ft)	Comments[a]
Patapsco	MD	Bloede	Denil	25	1 on 8	4	Under construction, DA = 304 SM
Patapsco	MD	Daniels	Denil	17	1 on 8	4	Under construction, original construction cost $356,000 DA = 265 SM
Elk Creek	MD	Elkton	Denil	5	1 on 8	3	Under construction, problems with building it, DA = 55 SM
Little Patuxent	MD	Fort Meade	Denil	5.5	1 on 6	3	Has observation window, DA = 27.5 SM
Winters Run	MD	Winters Run	Denil	5	1 on 6	3	DA= 55 SM
Tuckahoe Creek	MD	Tuckahoe	Denil	4	1 on 6	3	Under construction, reduced spacing to 18 in to help yellow perch, DA = 65 SM
Susquehanna	MD	Conowingo - H	West fish lift	36		8	Completed in 1972, interim trapping and trucking facility, Completed in 1991, trap and truck or lift fish to headpool, DA = 27100 SM (largest drainage basin on East Coast)
			East fish lift	94		12	
Chickahominy	VA	Walkers	2 Denils	3	1 on 8	3 (each)	In middle of river, requires flashboards to be up on right side, DA ≈ 250 SM
Herring Creek	VA	Harrison Lake	Denil	9.5	1 on 6	3	Problems downstream, has limited effectiveness, DA = 27 SM
Meherrin Creek	VA	Emporia - H	Fish lift	44		6	Completed in 1991, DA = 747 SM
James	VA	Browns Island	Breaches	4		25	Breaches cut into existing dam near left bank, Breaches cut into existing dam near left bank, DA ≈ 6775 SM
		Manchester				75	

[a]DA = drainage area; SM = square miles.

have been built and several pass up to 600,000 river herring annually. The projects have varying head and no two designs are similar. However, they work well and pass adequate numbers of herring to saturate the upstream spawning areas. Other types of fishways that are unique, and do not fit into any of the above categories are the chute type and the J-hook fishways that have been built in Maine. Again, each is site specific and operates under a very limited range. However, if proper adjustments are made to regulate the flow coming down through the fishway, they will pass a sufficient number of herring.

The final fishway type is the addition of a downstream hydraulic control weir with a notch. This would back up water into a culvert, allowing the upstream migrating fish to swim into the culvert and to pass upstream. In some instances several control weirs may be required. More than a 15 to 18 in drop per barrier is not recommended, although the 3 ft limit is within the swimming ability of *Alosa*. Many of these control weirs or small notched barrier dams are being implemented in culverts by the Maryland Department of Natural Resources.

Acknowledgement

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Potential Application of the Endangered Species Act to Anadromous *Alosa* of the East Coast of the United States: Process, Needs, and Constraints

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Abstract.—We evaluated the potential feasibility of application of the Endangered Species Act (ESA) to East Coast anadromous *Alosa* species through a review of actions taken in listing West Coast salmonid stocks and a survey of state and federal fisheries management agencies along the East Coast. Criteria used in listing salmonids appear to be applicable to *Alosa*. However, survey responses suggested that rigorous, quantitative data on stock status is very limited and virtually no information on genetic integrity of tributary *Alosa* stocks is available. Management agencies are, in general, not supportive of the application of the ESA to *Alosa* stocks, primarily due to reservations about the impacts which such an action would have on their management of the target species as well as fisheries for other species in which the target species is taken as by-catch. However, most agency staff were not familiar with the basis for or consequences of listing actions being taken on the West Coast. Benefits from listing, such as enhanced protection of critical habitats for anadromous *Alosa*, may merit increased efforts to develop the data and information necessary for initiating ESA listing actions in some cases.

The Endangered Species Act (ESA) was enacted in 1973 with the intent of preventing the extirpation of species which exist at critically low levels of abundance and are likely to become extinct without human intervention. The term "species" is applied in the ESA more broadly than its strict scientific definition, to include "...any subspecies of fish or wildlife or plants, and any distinct population segment of any species of vertebrate fish or wildlife which interbreeds when mature" (ESA Section 3). When the ESA was enacted, the single anadromous species named in the initial list of threatened and endangered species was the shortnose sturgeon *Acipenser brevirostrum* which was listed as an East Coast stock and not by any individual tributary population. For many years after initial enactment, the public awareness of the ESA was heightened as a result of the effect of its application to little known species such as the snail darter *Percina tanasi* on major development projects. The public attention attracted by listed charismatic megafauna such as the grey whale and whooping crane also enhanced public knowledge about and appreciation of the significance of the Act.

It was not until 1989 that the ESA was first applied to a single strain of an anadromous species, the Sacramento River winter chinook salmon (Nehlsen et al. 1991). Since that time, a number of other West Coast tributary-specific salmonid strains have been listed, and several East Coast Atlantic salmon strains have been identified as candidate species for listing. Despite apparent very low levels of numerous tributary stocks of anadromous *Alosa* along the East Coast, to date none of these strains or stocks have been considered to be potential candidates for listing under the ESA. The objective of this paper is to explore the potential basis for listing of various East Coast anadromous *Alosa* stocks as threatened or endangered, discuss the advantages and disadvantages of such listing, identify potential obstacles to such action, and, finally, assess the feasibility or likelihood of such listing occurring in the future.

Application of the Endangered Species Act to Anadromous Species

Marine, estuarine, and anadromous species are added to the list of threatened or endangered species by action of the Secretary of Commerce through the National Marine Fisheries Service (NMFS), in response to petitions requesting such action from any party. A positive determination by the Secretary results in the U. S. Fish and Wildlife Service (USFWS) adding that species to the federal List of Endangered and Threatened Wildlife. Numerous states have enacted legislation paralleling the federal ESA and have state-specific lists of threatened and endangered species. In general, these lists are inclusive of federally-listed species but more comprehensive, often including species which are considered threatened or endangered locally but not over their entire range of occurrence.

The consequence of federal listing is that the species is generally protected from take, although, as noted by Nehlsen et al. 1991, certain exceptions may be granted for those species listed as threatened. In addition, federal agencies are required to ensure that their actions will not jeopardize the continued existence of the listed species or adversely impact critical habitat for the species. Typical federal and state actions which are impacted by the ESA are the issuance of licenses and permits for major projects or facilities (e.g., the licensing of a hydroelectric facility by the Federal Energy Regulatory Commission, or the issuance of a Section 404 Wetlands permit by the U.S. Army Corps of Engineers).

Bjornn and Homer (1980) presented a number of criteria which were applied to Pacific salmonids to identify candidate stocks for listing. They defined an endangered population as one with a persistent negative production rate (i.e., less than one adult returning to spawn per spawner), with no return to a higher rate envisioned. A threatened population was defined as one with a declining production rate, a ratio of approximately one adult returning to spawn per spawner, and little likelihood of an increasing adult production rate under existing conditions. The other criteria which must be taken into account is related to the definition of "species" presented in the ESA and noted above. The term "...distinct population segment..." has been generally interpreted as meaning genetically distinct (Utter 1981). Given their similar migratory life history characteristics, it appears reasonable to accept the selection process and criteria by which Pacific salmonids were listed as a model for the potential listing of Atlantic *Alosa*.

Information Acquisition

The potential need for listing of any East Coast anadromous *Alosa* stock is clearly based on the status of the stock. Thus, in assessing the possible need for listing, we first sought information on the status of stocks throughout their range (any move to list an anadromous species would have to be supported with quantitative scientific data). In addition, we sought information on any special designations of *Alosa* stocks which had been conferred by a state agency that may dictate special conservation or habitat protection measures. Acquisition of this information was through a mail survey of fisheries management personnel in all coastal states from Maine to Florida, and verbal inquiries of USFWS and NMFS fisheries staff. The survey was purposely directed at fisheries management staff as opposed to those staff responsible for the administration of existing threatened and endangered species programs to more accurately establish management attitudes and their perception of obstacles to implementing a listing effort. The stock status survey was done concurrently and in coordination with that being conducted by Rulifson (1994) in developing stock status information but taking a somewhat different perspective from that of Rulifson.

Information sought in the survey included: statewide status of stocks; availability of reliable information on stock status and abundance; identification of any anadromous *Alosa* which are presently listed or have been designated for special protection; identification of any tributary-based management programs; degree of familiarity with listing efforts and controversies relating to West Coast salmonids; identification of species which might benefit from listing; and view of the agency on the merits or disadvantages of listing. Any additional relevant comments or observations were also requested.

Survey Findings

Table 1 presents a summary of only those survey responses which indicated *Alosa* species that were considered to be at extremely low levels of abundance or extinct, or the status of which was unknown. These status categories are the only ones summarized here, since the issue being addressed is potential listing. Rulifson (1994) presents a more comprehensive stock status summary for anadromous *Alosa* species at all abundance levels and for all East Coast states. Survey forms were returned by all states except North Carolina; however, within a single survey form, not all questions were answered, which is why all states do not appear in the tabular summaries presented here.

TABLE 1.— Summary of agency responses regarding East Coast anadromous *Alosa* species with low or uncertain status.

Species	Extremely Low or Extinct	Uncertain
American shad	DC, MD, VA	
Hickory shad	DC, VA, MD	MA, RI, CT, NY, NJ, PA, DE, SC, GA
Blueback herring	VA	ME, PA, DE
Alewife	SC, VA	NY, PA, DE

As is evident from these responses and those presented by Rulifson (1994), many of the agencies are uncertain of stock status. These responses are consistent with the state of knowledge on stock status presented in the ASMFC Fishery Management Plan for the Anadromous Alosa Stocks of the Eastern United States (1985). In limited verbal follow-up inquiries, it is evident that the availability of *quantitative* and scientifically rigorous stock status information is even more limited than suggested by the general survey responses. Virtually the only *Alosa* stocks for which quantitative status data exists are American shad *Alosa sapidissima* stocks in the Connecticut River, the upper Chesapeake Bay and the Savannah River, and river herring *A. aestivalis* and *A. pseudoharengus* stocks on systems where fish passage is monitored or where harvests occur at fish passage facilities (ASMFC 1985). Examples of such systems are the Lamprey River in New Hampshire and the numerous small stream river herring fisheries in a number of the New England states. The need for stock status information and the lack of such data was noted as a major deficiency in the management of East Coast *Alosa* stocks in the ASMFC Supplement to the Fishery Management Plan for American Shad and River Herring (1988). The characterization by most states of species status being "extremely low/extinct" was based most often on the observed absence of the species in harvests and surveys.

Three states currently have listings for certain *Alosa*: Maryland (American shad, hickory shad *A. mediocris* - "in need of conservation"); District of Columbia (American shad, hickory shad - "endangered"); and Pennsylvania (hickory shad - "candidate species for protection"). The designations of "in need of conservation" and "candidate species for protection" permit the state agencies to take certain management measures which they would otherwise be precluded from implementing. However, they are not related in any way to the designations of "threatened" or "endangered" as defined in the ESA or in similar state regulations.

Table 2 presents a summary of the various states' opinions as to the merits of application of the Endangered Species Act to anadromous species along the East Coast. As is evident from the table, in general, the state management agencies are, at the present time, not enthusiastic advocates of ESA application to anadromous *Alosa* stocks. Additional comments provided on the survey forms suggested that opposition to the concept was, in some cases, extremely vehement. However, it was also evident that very few of the *Alosa* fishery managers were familiar with the factors leading to listing of the West Coast salmonids or with the process by which those stocks were listed.

Objections to and Concerns with Listing

The various objections to listing reflect many of the difficulties which those agencies and personnel responsible for management of exploited resources anticipate might arise if listing of *Alosa* stocks were attempted. In addition, the feasibility of application of the ESA, as presently worded, to *Alosa* stocks, given the present state of knowledge of much of the species' life history characteristics, was questioned. Most *Alosa* management personnel were either not aware or only generally aware of the process of and controversies associated with the listing of salmonids on the West Coast. The constraints on ESA application could be grouped into a number of broad categories:

TABLE 2.— Views of the merit of ESA application from those states offering an opinion.

State	Survey Response		
	Yes	No	Maybe
Maine	• (Atlantic salmon)		
New Hampshire	• (Atlantic salmon, American shad)		
Rhode Island		•	
Pennsylvania		•	
Delaware			• (Shortnose sturgeon)
Maryland		•	
Virginia			• (*Alosa*)
South Carolina	•		
Florida		•	

Tributary stocks. Hickory shad, alewife, and blueback herring utilize much smaller river tributaries as spawning areas than any of the West Coast salmon stocks which have thus far been listed. In some river systems, a particular *Alosa* species appears to still be abundant in some lower order tributaries of the system while being absent in others. The precision of homing of *Alosa* species to individual tributaries is generally believed to be lower than that of salmonids (ASMFC 1985). Virtually no genetic studies have been done to establish the genetic integrity of *Alosa* stocks in different river systems or in different tributaries within river systems. Given these circumstances, the concept of tributary-specific stocks of anadromous *Alosa* appears to be unsupported by existing data and information and thus would not provide a basis for application of ESA.

Inadequacy of Stock Status Information. Most states lack quantitative stock status information. While many are confident, based on incidental and anecdotal information, that current stock levels of many *Alosa* species in many river systems are very low, they lack the hard data which would be required to support the view that these stocks are "threatened" or "endangered." Thus, the scientific basis for a listing action in most cases is relatively weak.

Impact of Listing on Management Programs. ESA listing of an individual *Alosa* stock is viewed with trepidation by those state agencies responsible for the management of harvest of the prospective listed species as well as fisheries for other species which take the prospective species as by-catch. If an individual stock of a particular *Alosa* species were listed, concerns were raised that any fishery taking *Alosa* would have to be severely restricted, due to the well documented mixing of stocks when not on the spawning grounds (ASMFC 1985) and the inability to distinguish different stocks in non-spawning ground fisheries. *Alosa* are also frequently taken in fisheries targeting other species, although in low numbers. Designation of a particular stock as endangered might require the cessation of such fisheries, under the mandate that an endangered species not be subject to take. In general, the view of most fisheries managers was that listing would limit the flexibility of their agency in implementing conservation measures and create severe difficulties in carrying out their broader responsibility for the management of all exploited resources. However, as noted above, this view was expressed in the absence of detailed knowledge of how these issues were resolved in the case of West Coast salmonids. For example, with regard to concerns about impacts of listing on mixed stock ocean fisheries, this issue was circumvented in the case of Columbia River listed salmon stocks by designating as critical habitat only the riverine environment. Thus, no actions had to be taken to address incidental harvest in the ocean (C.D. Williams, personal communication).

Listing as a Misdirected Solution to Species Conservation. The view was expressed by a number of respondents that ESA listing represented a "short-sighted" approach to species conservation and protection because it focused on a single species rather than targeting the preservation and enhancement of the riverine ecosystems and habitats which are essential to the species' survival and recovery.

"Frivolous" Application of ESA. Several respondents suggested that the application of ESA to individual tributary stocks of *Alosa* would constitute a "frivolous" application of the concept, since there is little basis for the view that any of the East Coast *Alosa* species are currently in danger of extinction. From this perspective, attempts to apply ESA to anadromous *Alosa* might be viewed by the public and various interest groups simply as a means of accomplishing other, unstated "anti-growth" or "anti-development" objectives. This in turn might serve to weaken public support for the entire ESA concept.

Conclusions

This review of the process by which the ESA could be applied to anadromous *Alosa* stocks and the views of the state agencies which would be responsible in a number of different ways for implementing the actions required as a result of ESA listing suggest that listing of East Coast *Alosa* stocks is, at present, unlikely. A number of different factors provide the basis for this conclusion:

Genetic Stock Characterization. Application of ESA to tributary salmonid stocks has been supported in all cases by genetic stock characterization data. No comparable data exist for anadromous *Alosa* stocks. Limited studies have been conducted on American shad stocks near the mouth of the Chesapeake Bay as part of an investigation into potential impacts of ocean intercept fisheries on the restoration of Susquehanna River shad stocks (R. Chapman, Univ. South Carolina, personal communication). No other data exist to support or refute the concept of genetically distinct tributary stocks of any of the four anadromous *Alosa* species being considered here.

Absence of Quantitative Stock Status Data. The absence of rigorous, quantitative stock status data severely reduces the probability of success of any listing petition. This is particularly true when potential sources of data, such as commercial harvest records, are not presently available due to harvest restrictions imposed to protect depressed *Alosa* stocks. In addition, the absence of historical stock status data creates a circumstance in which any current status data cannot be placed in context as a basis for concluding that a stock is currently severely depressed or threatened.

Lack of Support of Fisheries Management Agencies. The most general basis for the absence of support stems from the view that the agency would lose flexibility in management and also lose some degree of control to federal or non-management state agencies, and thus be prevented from performing their assigned management responsibilities. In addition, the specter of having to constrain mixed-stock or by-catch fisheries and thus impose substantial socio-economic hardship on harvesters in order to protect a species the status of which is questionable adds to the doubts which managers have about the wisdom of ESA application to East Coast anadromous *Alosa*.

Despite the reticence on the part of fishery managers, there are several possible advantages to ESA listing of depleted *Alosa* stocks. One is that listing is perhaps the most effective means of elevating the regulatory and public visibility of a depressed stock which no longer has major economic value. Such increased visibility ensures that any type of action which might affect that stock, whether it be habitat modification or changes in fisheries regulations, would have to be evaluated with regard to its potential impact before it would be implemented. For a depressed stock not listed, the level of scrutiny given such actions is often relatively low. In addition, ESA listing, because of the requirement that critical habitat be protected, provides one means by which habitat protection for the benefit of an exploited species can be rigorously applied and supported by regulation. At present, most fisheries management agencies deal only with regulation of harvest and have relatively limited impact on habitat modification actions.

It appears unlikely that any actions will be forthcoming in the near future to designate any East Coast *Alosa* stock as threatened or endangered under the Endangered Species Act, despite the possible advantages. While the possibility of listing is limited by the lack of information and data available to support such an action and the lack of enthusiasm for the approach on the part of many of the agencies, it is also, to a large extent, due to East Coast agencies and environmental groups being generally unfamiliar with the application of the ESA to tributary-specific anadromous fish stocks. If listing were to be pursued, it would be most feasible for those stocks being monitored on a regular basis, such as various river herring stocks which are monitored during spawning runs at fish passage facilities in New England. Significant declines in spawning stock size over a period of years, when evaluated within the context of historical run sizes, could be used to assess whether the individual stocks meet the criteria for salmonid listing developed by Bjornn and Homer (1980), such as a persistent negative production rate.

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Status of Anadromous *Alosa* Along the East Coast of North America

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Abstract.—Concern about decreased harvest of anadromous *Alosa* along the eastern seaboard of the USA and Canada has resulted in consideration of stricter stock management measures by state, federal, and provincial agencies. The objective of the study described herein was to ascertain the status of individual populations of four *Alosa* species by results obtained from a questionnaire administered in 1992 to fishery managers in 15 coastal states and two Canadian provinces. Questionnaire responses included information for 145 rivers in Canada (New Brunswick to Nova Scotia), 155 rivers in New England (Maine to Connecticut), 175 rivers in mid-Atlantic states (New York to Virginia), and 47 rivers in south Atlantic states (North Carolina to Florida). Knowledge of population status was often more complete on those populations currently targeted and those in past years for stock assessment studies. Approximately 34% of the American shad *Alosa sapidissima* populations in New Brunswick and Nova Scotia are declining with an additional 24% at a low stable or threatened condition. Nearly 3% have been extirpated. About 18% of the New England populations are increasing, due primarily to strict harvest regulations and stocking efforts. An additional 25% of the populations are stable, but almost 20% are low stable but threatened and 5% have been extirpated. In the mid-Atlantic states, over 21% of the populations have been extirpated and almost 18% are low stable or threatened. Approximately 54% of the south Atlantic populations are stable. Stock status of hickory shad *A. mediocris* is poorly documented. In eastern Canada, most alewife *A. pseudoharengus* populations (86%) are in decline. The majority (56%) of New England alewife populations are stable; alewife status for the mid-Atlantic states was unknown for 66% of the runs. North Carolina is the southern limit of commercially-important alewife populations; 55% of the runs in North Carolina are in decline and the status of the remainder is unknown. The status of most blueback herring *A. aestivalis* populations (79%) in eastern Canada is not well-documented. Approximately 66% of the blueback runs in New England are stable. About 28% of the mid-Atlantic blueback runs are in decline, and 27% are stable. Nearly 24% of south Atlantic blueback runs are in decline, and 15% are low stable but threatened; the status of 44% of the runs was unknown. Dams, inadequate fishway facilities, and poor control of water releases from reservoirs are the primary contributors to declining stocks in Canada and New England. South of New England, dams and fishways are important but other factors resulting in poor water quality are more numerous: thermal effluents, low oxygen, sewage, sedimentation, turbidity, and non-point source pollution. Activities responsible for water quality changes include, but are not limited to: channelization, dredge and fill, and road and residential construction.

State and federal U.S. agencies, and Canadian provincial and federal agencies, have monitored the status of anadromous *Alosa* stocks along the North American eastern seaboard for decades. Three *Alosa* species are of primary management interest: American shad *Alosa sapidissima*, alewife *A. pseudoharengus*, and blueback herring *A. aestivalis*. Alewife and blueback herring are similar in appearance and life history, and are marketed together commercially as river herring in the U.S. and gaspereau in Atlantic Canada. American shad is both commercially and recreationally important, and is marketed together with the hickory shad *A. mediocris*, a relatively unstudied anadromous *Alosa* species.

Early monitoring efforts were associated with commercial catch statistics; more recently, monitoring efforts have included state-federal cooperative projects initiated to assess trends in the stock status of numerous anadromous *Alosa* runs in specific river systems. One management approach underway in Chesapeake Bay is an attempt to assess habitat quality of streams, and to upgrade habitats in those streams to improve *Alosa* runs (E. Pendleton, U.S. Fish and Wildlife Service (USFWS), personal communication). Restoration and improvement of anadromous fish habitat is one aspect of the Coastal America program, a coordinated effort involving agencies responsible for stewardship of coastal living resources: the USFWS, the U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, the U.S. Geological Survey, the Minerals Management Service, the National Oceanic and Atmospheric Administration, and the National Park Service. One objective of the program is to identify obstructions and blockages to migratory fishes such as dams and culverts and to assist with their removal (M. Wicker, USFWS, personal communication).

Declines in the *Alosa* commercial harvest in the 1970's, coupled with the extensive ocean migratory pattern exhibited by *Alosa*, resulted in a perceived need by the Atlantic States Marine Fisheries Commission (ASMFC) for an interstate fishery management plan (Richkus and DiNardo 1984). By 1982, an action plan was established by ASMFC to meet this objective (ASMFC 1985). An additional consideration was the developing offshore fishery for *Alosa* (ASMFC 1985), which is either a bycatch intercept fishery from New Jersey northward, or a directed intercept fishery south of New Jersey to Florida (Harris and Rulifson 1989). The ASMFC's Shad and River Herring Science and Statistical (S & S) Committee has taken the position that no state should allow, or encourage, the development of an *Alosa* intercept fishery (H. Johnson, NC Division of Marine Fisheries, personal communication). Recently, the Virginia Marine Resources Commission imposed a total moratorium on *Alosa* harvesting from the Virginia waters of the Chesapeake Bay and its tributaries beginning in 1994 (regulation 450-01-0069), yet the state will allow the ocean intercept fishery to continue in a move contrary to the ASMFC plan.

One problem in implementing management plans for these species is that information for only selected streams is available, and the remaining runs are largely unstudied. The objective of the study described herein was to document the status of *Alosa* populations on a river-by-river basis from eastern Canada to Florida to assist in identifying information gaps in formulating management plans. Identifying the possible causative factors involved in declining or extirpated populations was also of interest.

Methods

In 1992, a questionnaire was sent to those state fishery management personnel that were members of the ASMFC Shad and River Herring S & S Committee asking their opinions on the status of stocks and possible causes for declining populations. A similar but more detailed survey was conducted in 1980 for coastal states along the southeast Atlantic and Gulf of Mexico (Rulifson et al. 1982a; 1982b). The first part of the questionnaire asked the state agencies to identify the river systems within or bordering their state that were important to any of the four anadromous *Alosa* species. For each river system and species combination listed, personnel were asked their opinions on the status of the population using six possible answers: increasing, stable, decreasing, threatened, no longer present (extirpated), or status unknown. Several states responded by writing in a seventh category - stable but threatened - indicating that long-term watershed problems were preventing the re-establishment of populations to historical levels. Canadian rivers were assessed by personnel of Fisheries and Oceans Canada using the same questionnaire.

The second portion of the questionnaire was a matrix of the river systems listed in part one of the questionnaire, with 21 possible contributors to declining populations. Possible choices of physical disturbances were: channelization, dredge and fill projects, bulkheading, dams and impoundments, industrial water intakes, location of industrial discharges, road construction, and a blank for adding other physical disturbances. Possible choices of chemical disturbances included: acid rain, chemical pollution (e.g., heavy metals), thermal effluents, turbidity, low oxygen levels, sewage outfalls, and a blank for other chemical factors. Habitat management choices were: inadequate fishway facilities, inadequate control of water releases from dams, reduced freshwater input to estuaries, reduction in spawning habitat, reduction in nursery areas, poor food availability, spawning areas too accessible to fishermen, poor water quality, and a blank for other habitat management problems. For each river/disturbance combination, one of four responses about the disturbance was possible: very important contributor to declining stocks, important, inadequate information, and does not contribute to declining stocks. Information was compiled and tabulated, with general results summarized by region.

Life history information for each species was summarized. Many of the streams are not utilized by all four *Alosa* species; therefore, knowledge of the species range and habitat requirements in fresh waters was needed to provide a context for interpreting survey results.

Results and Discussion

Questionnaire responses were received for all 15 Atlantic coastal states and two Canadian provinces. Information on *Alosa* status was provided for 422 rivers: 145 in Atlantic Canada (New Brunswick to Nova Scotia), 155 in New England (Maine to Connecticut), 175 in the mid-Atlantic states (New York to Virginia), and 47 in south Atlantic states (North Carolina to Florida). Not all *Alosa* species were present in every river, and responses on status of stocks were more complete on those populations currently targeted and those in past years for fisheries management studies.

American Shad

American shad range from Labrador (Dempson et al. 1983) and the eastern New Brunswick rivers draining into the Gulf of St. Lawrence, to Florida rivers draining into the Atlantic Ocean. Spawning takes place in the main channels of coastal streams in fresh water. Gametes are broadcast into the water column; the demersal, non-adhesive eggs are fertilized and develop as they are being carried by currents downstream. After hatching, larvae drift downstream to disperse in fresh or brackish water after reaching a sufficient size. At 20 to 30 mm total length (TL), juveniles form schools in deeper non-tidal waters away from shorelines. By autumn, juveniles 50-70 mm TL have emigrated to estuarine areas, after which they live in the ocean for three to five years before returning to their natal streams as adult spawners (Jones et al. 1978). Shad populations of U.S. and Canadian origin mix in the Bay of Fundy, Canada, during their extensive summer migrations (Melvin et al. 1986; Dadswell et al. 1987). Spawning activity follows a south to north temporal progression beginning in December in Florida and occurring in May, June or even July in the Canadian Maritimes (Scott and Scott 1988).

The commercial harvest of American shad peaked in the 1890's, but declined drastically from 1900 to 1915 resulting in vigorous efforts by fisheries agencies to reverse the trend. After World War II, the reduced stocks and reduced demand for the species as a food fish relegated the fishery to a minor component of total coastal landings (St. Pierre 1979).

In Atlantic Canada, only 26% of the 145 reported rivers contain shad (Table 1); none of the populations are increasing in size (Table 2). Most of the shad rivers are located along the coasts of the Bay of Fundy and Gulf of St. Lawrence; few shad runs are located along the Atlantic coast of Nova Scotia. Nearly 58% of Canadian shad populations were believed to be in decline or threatened. The status of 37% of the runs was unknown, primarily those shad runs in the Gulf of St. Lawrence.

In New England, 36% of the 155 reported rivers have shad populations (Table 3), nearly 43% of which were considered stable or increasing in size and only 1.8% declining or threatened (Table 2). A number of these shad runs currently are in restoration programs involving stock enhancement or habitat improvement. In 1992, rivers receiving adult shad transferred from the Connecticut River at Holyoke, Massachusetts, include the Kennebec and Androscoggin rivers in Maine, the Exeter River and the Merrimack River and its tributaries in New Hampshire, and the Charles River in Massachusetts. Two populations in Rhode Island and one in New Hampshire were believed extirpated.

Approximately one-fifth of the 56 reported shad runs in the mid-Atlantic states may be extirpated, and 32% are in decline or threatened (Table 2). About 14% of the runs are increasing, primarily the result of habitat improvement and stock enhancement programs. The Susquehanna River shad restoration program involves stocking fry upstream mainly in the Juniata River and a smaller number in the Susquehanna below Conowingo Dam, and in lifting adult fish over the Conowingo Dam during the spring spawning run. In 1992, fry used in the stocking program were of Delaware, Hudson, and Connecticut river origin. Recaptures of juveniles indicate that Hudson River fry survive in the Susquehanna at a higher rate than juveniles of Delaware and Connecticut origin (R. St. Pierre, USFWS, unpublished data).

Many of the 31 reported shad runs in the Carolinas are stable, but slightly more than one-half of Georgia's shad runs may be in decline (Table 2). Results of the 1992 survey were compared to results from a similar survey conducted in 1980. Of the 24 changes in responses, 52% were of populations shifting from a known status in 1980 to status unknown in 1992 (Table 4). This trend reflects the lack of time and personnel necessary to maintain monitoring programs while meeting demands of fishery research needs in other areas.

Alewife

Alewife range from Newfoundland (Winters et al. 1973), eastern New Brunswick and Nova Scotia (Table 1) through New England and the mid-Atlantic states (Table 3) to North Carolina (Table 4). Populations south of Albemarle Sound are not well documented but the range extends into South Carolina (Berry 1964). In southern locations, the adhesive eggs are typically spawned in shallow, heavily vegetated streams and floodplains at a location slightly upstream of blueback herring spawning activity. In Canada, alewife eggs have been collected from areas of river rapids (Scott and Scott 1988). Larvae form schools one to two weeks posthatch (at about 10 mm TL) and remain in the vicinity of spawning sites until summer, when, as juveniles, they pass into estuarine areas. Overwintering is in seaward locations of estuaries or in the coastal ocean. Adults overwinter in the coastal ocean. Spawning has a temporal progression, starting in March in North Carolina, April in Bay of Fundy rivers, and June in Gulf of St. Lawrence streams (Scott and Scott 1988).

TABLE 1.— Status of anadromous *Alosa* fish species in streams of Atlantic Canada in 1992. 0 = never present; 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = no longer present; 6 = status unknown; 7 = stable but threatened.

Province and water body	American shad	Alewife	Blueback herring	Hickory shad
New Brunswick, Gulf of St. Lawrence (6)				
Restigouche River	6	6	6	
Pokemouche River	6	2	2	
Tracadie River	6	2	2	
Miramichi River	2	2	2	
Kouchibouguac River	6	2	2	
Richibucto River	6	2	2	
Nova Scotia, Gulf of St. Lawrence (8)				
River Phillip	6	2	2	
West River (Pictou Co.)	6	2	2	
Middle River (Pictou Co.)	6	2	2	
East River (Pictou Co.)	6	6	6	
West River (Antigonish Co.)	6	2	2	
South River (Antigonish Co.)	6	2	2	
Margaree River	6	2	2	
Cheticamp River	0	0	0	
Nova Scotia, Atlantic Coast (69)				
North Aspy River	0	3	6	0
Ingonish River	0	3	6	0
Indian Brook	0	3	6	0
Barachois River	0	3	6	0
North River (Victoria Co.)	0	3	6	0
Baddeck River	0	3	6	0
Middle River (Victoria Co.)	0	3	6	0
Aconi Brook	0	3	6	0
Mira River	0	3	6	0
Catalone River	0	3	6	0
Lorraine River	0	3	6	0
Gerratt Brook	0	3	6	0
Salmon River (Cape Breton Co.)	0	3	6	0
Gaspereau River (Cape Breton Co.)	0	3	6	0
Framboise River	0	3	6	0
Marie Joseph River	0	3	6	0
Grand River	0	3	6	0
River Tillard River	0	3	6	0
Inhabitants River	0	3	6	0
Clam Harbour	0	3	6	0
Guysborough River	0	3	6	0
Salmon River (Guysborough Co.)	0	3	7	0
Cole Harbour	0	3	6	0
Larry's River	0	3	6	0
New Harbour	0	3	6	0
Issac's Harbour	0	3	6	0
Country Harbour	0	3	6	0
Indian River	0	3	6	0
Gegogan River	0	3	6	0
St. Mary's River	7	3	7	0
Gaspereau Brook	0	3	6	0
Liscomb River	0	3	6	0
Ecum Secum River	0	3	6	0
Necum Teuch (Smith Brook)	0	3	6	0
Moser River (Halifax Co.)	0	3	6	0
Quoddy River	0	3	6	0
Salmon - Port Dufferin River	0	3	6	0
East River Sheet Harbour	0	3	6	0

TABLE 1.— continued.

Province and water body	American shad	Alewife	Blueback herring	Hickory shad
West River Sheet Harbour	0	3	6	0
Taylor Bay Brook	0	3	6	0
Kirby River	0	3	6	0
Tangier River	0	3	6	0
Ship Harbour	0	3	7	0
Salmon River (Halifax Co.)	0	3	7	0
Musquodoboit River	3	3	7	0
Chezzetcock River	0	3	6	0
Three Fathom Harbour Brook	0	3	6	0
Rocky Run	0	3	6	0
Salmon River (Lawrencetown Lake)	0	3	6	0
Little Salmon River (Lake Major)	0	3	6	0
Sackville River	0	1	6	0
Nine Mile River	0	3	6	0
Ingram River	0	3	6	0
East River (Lunenburg Co.)	0	3	6	0
Middle River (Lunenburg Co.)	0	3	6	0
Gold River	0	3	6	0
Martins Brook	0	3	6	0
Mushamush River	4	3	6	0
LaHave River	3	3	6	0
Petite Riviere	0	3	6	0
Medway River	4	3	0	0
Mersey River	0	3	6	0
Broad River	0	3	6	0
Sable River	0	3	6	0
Jordan River	0	3	6	0
Roseway River	0	3	6	0
Clyde River	0	3	6	0
Barrington River	0	3	6	0
Tusket River	7	3	3	0
Nova Scotia, Fundy Coast (30)				
Salmon River (Digby Co.)	0	3	6	0
Sissiboo River	0	3	0	0
Bear River	0	3	0	0
Lequille River	0	3	0	0
Round Hill River	0	3	0	0
Paradise Brook	0	3	0	0
Annapolis River	3	3	0	0
Nictaux River	0	3	0	0
Cornwallis River	0	3	0	0
Gaspereau River (Kings Co.)	7	3	0	0
St. Croix River (Hants Co.)	3	3	6	0
Kennetcook River	3	3	6	0
Shubenacadie River	3	3	7	0
Stewiacke River	3	3	7	0
Salmon River (Colchester Co.)	0	3	0	0
North River (Colchester Co.)	0	3	0	0
Chiganois River	0	3	0	0
Debert River	0	3	0	0
Folly River	0	3	0	0
Great Village River	0	3	0	0
Portapique River	0	3	0	0
Bass River (Colchester Co.)	0	3	0	0
Little Bass River	0	3	0	0
Economy River	0	3	0	0
Harrington River	0	3	0	0
Diligent River	0	3	0	0
Apple River	0	3	0	0
River Hebert	3	3	6	0

TABLE 1.—continued.

Province and water body	American shad	Alewife	Blueback herring	Hickory shad
Nova Scotia, Fundy Coast—cont.				
Maccan River	7	3	6	0
Napan River (Cumberland Co.)	7	3	6	0
New Brunswick, Fundy Coast (32)				
Tantramar River (LaPlanche)	7	3	0	0
Demoiselle River	0	3	6	0
Crooked Creek	0	3	6	0
Shepody River	0	3	6	0
West River (Albert Co.)	0	3	6	0
Alma River	0	6	6	0
Pointe Wolfe River	0	6	6	0
Coverdale River	0	6	6	0
Turtle Creek	0	6	6	0
Weldon Creek	0	6	6	0
Pollett River	0	0	6	0
Petitcodiac River	4	4	4	0
Big Salmon River	0	0	0	0
Irish River	0	0	0	0
Mosher River (Saint John Co.)	0	3	6	0
Black River (Saint John Co.)	0	3	6	0
Hammond River	3	3	6	0
Little River (Saint John Co.)	0	3	6	0
Kennebecasis River	3	3	6	0
Saint John River	3	3	6	0
Nerepis River	0	3	6	0
New River	0	3	6	0
Pocologan River	0	3	6	0
Magaguadavic River	0	3	6	0
Digdeguash River	0	3	6	0
Waweig River	0	3	6	0
St. Croix River (Charlotte Co.)	5	3	0	0
Canaan River	3	3	3	0
Oromocto River	3	3	3	0
Salmon River (Queens Co., N.B.)	0	3	3	0
Nashwaak River	6	3	3	0
Keswick River	6	3	3	0

The status of alewife populations in Nova Scotia and New Brunswick was well documented. Nearly 86% of the 141 reported alewife runs are in decline, none of which are reported for the Gulf of St. Lawrence (Table 5). Gulf of St. Lawrence populations are stable. There are numerous rivers in the province of Prince Edward Island (Gulf of St. Lawrence) that have alewife runs but information on these populations, other than commercial landings by district, is lacking (G. Chaput, personal communication).

Approximately 56% of New England alewife runs are stable (Table 5), but stock restoration efforts by habitat improvement and supplementation programs have increased alewife populations in several New England rivers. Construction of permanent upstream and downstream fish passage facilities at hydroelectric dams, combined with transplanting adult Royal River alewives, is being used in Maine to restore historical alewife runs, especially in the Kennebec and Androscoggin rivers. However, 25 of the 35 Maine alewife runs are in decline or in stable but threatened condition. New Hampshire is stocking the Cocheco River with river herring from various Maine rivers. In 1992, Massachusetts continued fishway construction and repair, and stocked 16 different river systems with Monument River alewife to re-establish runs or augment resident populations. Several Rhode Island streams are being stocked with adult alewives from the Herring and Agawam

TABLE 2.— Number of American shad runs of each stock status category along the east coast of North America. Stock status: 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = extirpated; 6 = unknown; 7 = low stable but threatened.

			Stock status						
State or region	Rivers reported	Rivers with runs	1	2	3	4	5	6	7
Gulf of St. Lawrence	14	13	0	1	0	0	0	12	0
Nova Scotia,									
Atlantic Coast	69	6	0	0	2	2	0	0	2
Bay of Fundy	62	19	0	0	11	1	1	2	4
Total Canada	145	38	0	1	13	3	1	14	6
Percent reporting		26.2	0	2.6	34.2	7.9	2.6	36.8	15.8
Maine	35	24	2	1	0	0	0	10	11
New Hampshire	8	8	3	0	0	0	1	4	
Massachusetts	15	11	3	5	0	0	0	3	
Connecticut	75	8	0	8	0	0	0	0	
Rhode Island	22	5	2	0	1	0	2	0	
Total New England	155	56	10	14	1	0	3	17	11
Percent reporting		36.1	17.9	25	1.8	0	5.4	30.4	19.6
New York	1	1	0	1	0	0	0	0	
New Jersey	115	19	3	1	0	0	4	11	
Delaware	13	4	4	0	0	0	0	0	
Maryland	25	15	1	0	0	5	4	0	5
Pennsylvania	4	4	4	0	0	0	0	0	0
Virginia	17	13	0	2	7	0	1	3	
Total Mid-Atlantic	175	56	8	4	8	5	12	14	5
Percent reporting		32	14.3	7.1	14.3	8.9	21.4	25	8.9
North Carolina	20	17	0	11	0	0	0	6	
South Carolina	14	14	1	9	1	0	0	3	
Georgia	7	7	0	3	4	0	0	0	
Florida	6	5	0	0	0	0	0	5	
Total South Atlantic	47	43	1	23	5	0	0	14	0
Percent reporting		91.5	2.3	53.5	11.6	0	0	32.6	0

rivers in Massachusetts. At least three historical alewife runs in Rhode Island may have been extirpated.

The status of a large portion of the alewife runs in the mid-Atlantic states was unknown, particularly in New Jersey (Table 5). Only Delaware reported stable runs in a majority of rivers. Delaware is developing a restoration plan to enhance selected river herring runs in small tidal rivers, nearly all of which were impounded to provide power for grist mills. The old dams are impediments to anadromous *Alosa* but provide excellent recreational fishing opportunities. An *Alosa* fish passage pilot study is being conducted in the Broadkill River at Milton, Delaware, using a portable upstream/downstream fishway to Wagamons Pond (R.W. Miller, unpublished data). The Conowingo Dam fishlift on the Susquehanna River collected 3,629 alewife in 1992 (R. St. Pierre, unpublished data); this population was reported as not present in Table 1. In Virginia, alewife have not successfully negotiated the breaches over Williams Dam on the James River.

North Carolina is the southern limit of commercially-important alewife populations. The canals of Lake Mattamuskeet, which border the Albemarle and Pamlico sounds, support small commercial fishery operations. Of the reported rivers in the Southeast, 55% of the runs were in decline and the status of the remainder was unknown. The status of six North Carolina populations changed to unknown since the survey was last conducted in 1980 (Table 4).

Blueback Herring

Blueback herring range from Cape Breton, Nova Scotia, to the Tomoka River in Florida. In southern streams, the somewhat adhesive eggs are broadcast-spawned in shallow, slow moving water, floodplains, rice fields (Christie 1978), and other heavily vegetated areas above tidal influence (Godwin and Adams 1969; Frankensteen 1976). Eggs are demersal in still water but pelagic in lentic water. In northern streams, blueback herring prefer spawning sites in fast water over hard substrate (Loesch and Lund

TABLE 3.— Status of anadromous *Alosa* fish species from Maine through Virginia in 1992. 0 = never present; 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = no longer present; 6 = status unknown; 7 = stable but threatened; a = present in low numbers; b = not thought to be self-sustaining; two numbers separated by a comma indicate two respondees.

State and water body	American shad	Alewife	Blueback herring	Hickory shad
Maine (35)				
Androscoggin River	1	1		
Kennebec River	1	1		
Damariscotta River	0	3		
St. George River	7	3		
Orland River	6	3		
Union River	7	1		
East Machias River	7	3		
Dennys River	6	3		
St. Croix River	7	1		
Penobscot River	7	1		
Cobbossee Stream	7	7		
Mousam River	6	7		
Royal River	7	1		
Presumpscot River	7	1		
Nequasset Lake	0	3		
Togus Stream	6	7		
Sheepscot River	6	3		
Sherman Lake	0	1		
Pemaquid River	6	3		
Medomak River	6	1		
Megunitook River	0	7		
Ducktrap River	6	1		
Passagassawaukeg River	0	7		
Goose River	0	7		
Patten Stream	0	3		
Card Mill Stream	0	3		
Flanders Stream	0	3		
Great Pond Stream	0	3		
Narraguagus River	2	3		
Pleasant River	6	3	6	
Orange River	0	7		
Pennamaquan River	7	3		
Boyden River	6	3		
Saco River	7	7		
Nonesuch River	7	7		
New Hampshire (8)				
Exeter River	1	2	2	
Lamprey River	6	2	2	
Cochcco River	1	1	1	
Oyster River	5	1	1	
Taylor River	6	3	3	
Salmon Falls River	6	6	6	
Merrimack River	1	1	1	
Winnicut River	6	6	6	
Massachusetts (15)				
Monument River	0	1	3	
Palmer River	2	2	6	
Indian Head River	2	2	6	
South River	2	2	6	
Taunton River	1	3	3	
Charles River	1	6	2	
Merrimack River	1	1	1	
Runnins River	2	2	6	
Stoney Brook	0	2	2	
Agawam River	6	2	2	
Back River	0	1	6	

TABLE 3.— continued.

State and water body	American shad	Alewife	Blueback herring	Hickory shad
Massachusetts — cont.				
North River	2	2	6	
Jones River	6	4	4	
Town Brook	0	3	6	
Mattapoisett River	6	1	1	
Rhode Island (22)				
Blackstone River	5	5	5	
Brickyard Pond Brook	0	1	1	
Woonasquatucket River	0	5	0	
Runnins River	3	2	6	
Buckeye Brook	0	2	0	
Princess Pond Brook	0	3	0	
Warwick Brook	0	3	0	
Kickamuit River	5	5	6	
Apponey Brook	0	2	0	
Easten Pond	0	3	0	
Hunts River	1	1	1	
Nonquit Brook	0	1	1	
Annaquatucket River	0	1	0	
Tunupus Pond	0	2	6	
Wesquage Pond Brook	0	3	0	
Quicksand Pond	0	3	0	
Gilbert Stuart Brook	0	2	0	
Briggs Marsh	0	6	0	
Saugertucket River	0	2	0	
Potter Pond Brook	0	3	0	
Charlestown Brook	0	3	0	
Pawcatuck River	1	2	6	
Connecticut (75)				
Byrum River	0	2	2	0
Horseneck River	0	2	2	0
Mianus River	0	2	2	0
Rippowam River	0	2	2	0
Noroton River	0	2	2	0
Norwalk River	0	2	2	0
Saugatuck River	0	2	2	0
Sasco Brook	0	2	2	0
Mill River	0	2	2	0
Ash Creek	0	2	0	0
Pequonnock River	0	2	2	0
Housatonic River	2b	2	2	6
Naugatuck River	0	2	2	0
Wepawaug River	0	2	0	0
Indian River	0	1	1	0
Oyster River	0	2	2	0
West River	0	2	2	0
Quinnipiac River	2a	2	2	6
Mill River	0	2	2	6
Farm River	0	2	2	0
Branford River	0	2	2	0
West River	0	2	2	0
East River	0	2	2	0
Hammonasset River	2b	2	2	0
Menumkestesuck River	0	2	2	0
Patchogue River	0	2	2	0
Oyster River	0	2	0	0
Connecticut River	2	2	2	6
Lieutenant River	0	2	2	0
Falls River	0	2	0	0

TABLE 3.— continued.

State and water body	American shad	Alewife	Blueback herring	Hickory shad
Connecticut — cont.				
Eight Mile River	0	2	2	0
Deep River	0	2	0	0
Chester Creek	0	2	2	0
Pattaconk River	0	2	2	0
Whalebone River	0	2	2	0
Salmon River	2a	2	2	0
Moodus River	0	2	2	0
Pine Brook	0	2	2	0
Higganum Creek	0	2	2	0
Mattabesset River	0	2	2	0
Coginchaug River	0	2	2	0
Roaring brook	0	2	2	0
Salmon Brook	0	2	2	0
Porter Brook	0	2	2	0
Hockanum Brook	0	2	2	0
Podunk River	0	2	0	0
Burnham River	0	2	0	0
Scantic River	0	2	2	0
Broad Brook	0	2	2	0
Farmington River	2a	2	2	0
Salmon Brook	0	2	2	0
Threemile River	0	2	0	0
Fourmile River	0	2	2	0
Bride Brook	0	2	0	0
Pattagansett River	0	1	0	0
Niantic River	0	2	0	0
Old Mill Brook	0	2	0	0
Latimer Brook	0	1	0	0
Thames River	2	2	2	6
Hunts Brook	0	0	2	0
Stony Brook	0	2	0	0
Billings Avery Brook	0	2	0	0
Trading Cove Brook	0	2	0	0
Yantic River	0	2	2	0
Poquetanuck Brook	0	2	2	0
Shetucket River	0	2	2	0
Poquonock River	0	2	0	0
Eccleston Brook	0	2	0	0
Mystic River	0	2	2	0
Whitford Brook	0	2	2	0
Copps Brook	0	2	0	0
Stony Brook	0	2	0	0
Anquilla Brook	0	2	0	0
Pawcatuck River	2	1	1	0
Shunock Brook	0	2	2	0
New York (1)				
Hudson River	2	2	1	6
New Jersey (115)				
Alloway Creek		6		
Assunpink Creek		6		
Atlantic County lup. b	1	6		
Back Creek		1		
Back Run		6		
Ballanger Creek		6		
Bass River		6		
Batsto River		2		
Beaver Creek		6		
Big Timber Creek	6			

TABLE 3— continued.

State and water body	American shad	Alewife	Blueback herring	Hickory shad
New Jersey — cont.				
Blacks Creek	5	6		
Bog Branch		6		
Buckshutem Creek		6		
Cedar Creek		6	6	
Cedar Swamp Creek	6	6		
Cohansey River	6	6	6	
Comptons Creek		6		
Cooper River	5			
Crosswicks Creek	6	1	1	
Davenport Branch		6		
Deal Lake Dam		2	2	
Deep Run		6		
Delaware River		2	2	
Doctors Creek		6		
Double Creek		6		
Doughty Creek		6		
Fenwick Creek		6		
Fiddlers Creek		6		
Flat Creek		6		
Fresh Creek		6		
Gibson Creek		6		
Gravelly Run		6		
Great Egg Harbor River	6	6		
Green Creek	5			
Greenies Sandwash		6		
Gunning River		6		
Hackensack River	6	6	6	
Hammonton River		6		
Hankins Brook		6		
Hooks Creek			6	
Jacobs Creek		6		
Jakes Branch		6	6	
Jeffreys Creek		6		
Jobs Creek		6		
Kettle Creek		6	6	
Metedeconk River		6		
Lawrence Brook		6		
Little Siver Lake		6		
Lockatong Creek		6		
Long Swamp Creek		6		
Mannington Creek		6		
Mantua Creek		2	1	
Manumuskin River		6		
Maurice River	1	2	1	
McNeals Branch		6		
Menantico Creek		6		
Mill Creek, C.R. Drainage		6	6	
Mill Creek, M.B. Drainage		6		
Mill Creek, T.R. Drainage		6		
Mill Run, M.R. Drainage		6		
Millstone River			1	
Miry Run		6		
Mullica River	6	6		
Muskee Creek		6		
Nacote Creek		6		
Negro Creek		6		
Nescochague Creek		6		
N.B. Beaverdam Creek		6		
N.B. Rancocas Creek		1		
N.B. Metedeconk Creek		6		
Oldmans Creek	6	6		
Parkway Pond, M.R. Drainage		6		

TABLE 3.— continued.

State and water body	American shad	Alewife	Blueback herring	Hickory shad
New Jersey — cont.				
Passaic River	6			
Patcong Creek		6		
Pine Brook		6	6	
Pochemus Brook		6		
Potter Creek		6		
Raccoon Creek	2	6	6	
Raccoon Ditch, S.C. Drainage		6		
Rancocas Creek	1			
Rapaupo Creek	5			
Raritan River	1	2	1	
Richmonds Branch		6		
Salem River	6	6		
Shenandoah Lake, S.B.M.R.		2		
Silver Bay Creek		6		
S.B. Beaverdam Creek		6	6	
S.B. Double Creek		6		
S.B. Metedeconk River			2	
S.B. Raccoon Creek		6	6	
S.B. Ranocas Creek		6		
S.B. Stouts Creek		6		
South River		6		
Steel Run		6		
Stephan Creek		6		
Stow Creek		6		
Swamp Brook		6	6	
Swimming River		6	6	
Third River		6		
Toms River		6	6	
Tuckance River		6		
Tuckerton Creek			6	
Tunes Branch		6		
Twilight Lane, M.R. Drainage		6		
Wading River		6		
Warner Mill Stream		6		
Watering Race Branch		6		
Watson Creek		6		
West Creek		6		
Whale Pond Creek		6		
White Marsh Run		6		
Willis Creek		6		
Woodbury Creek	6			
Wrangle Brook		6		
Wreck Pond Creek		6	6	
Pennsylvania (4)				
Susquehanna River	1	0	5	6
Delaware River	1	6	3	6
Schuylkill River	1	2	2	6
Lehigh River	1	0	5	0
Maryland (25)				
Potomac River	7	3	2	4
Patuxent River	3,4	2	2	4
South River	0	3	3	0
Severn River	0	3	3	0
Magothy River	0	5	5	0
Patapsco River	5	2	2	5
Middle River	0	0	0	0
Bird River	0	3	3	0
Bush River	7	2	2	6

TABLE 3.— continued.

State and water body	American shad	Alewife	Blueback herring	Hickory shad
Maryland — cont				
Gunpowder River	3,4	3	2	5
Susquehanna River	1,4	3	3	7
Northeast River	5	3	3	5
Bohemia River	7	2	2	6
Elk River	7	2	3	6
Sassafras River	5	3	3	6
Chester River	5	2	3	6
Miles River	0	0	0	0
Choptank River	3,4	2	3	3,4
Nanticoke River	7	1	1	3,4
Wicomico River	3,4	2	6	3,4
Manokin River	0	6	6	0
Big Annemessex River	0	0	0	0
Honga River	0	2	3	0
Fishing Bay	0	2	3	0
Pocomoke River	3,4	2	3	3,4
Delaware (13)				
Brandywine River	5	3	3	6
Christina River	5	2	2	6
Appoquinimink River	0	6	6	6
Blackbird River	0	6	6	6
Smyrna River	0	6	6	6
Leipsic River	0	3	3	6
St. James River	0	3	3	6
Murderkill River	0	2	2	6
Mispillion River	0	2	2	6
Broadkill River	5	2	2	6
Cedar Creek	0	2	2	6
Indian River	0	0	0	6
Nanticoke River	3	2	2	4
Virginia (17)				
Meherrin River	2	0	2	0
Nottoway River	2	2	2	2
Blackwater River	0	0	2	0
James River	3,3	3,3	3,3	2,3
Nansemond River	5	5	5	5
Chickahominy River	3,6	3,3	2,3	6,3
Appomattox River	3	3	3	6
Pagan River	0	6	6	0
York River	3,3	3,3	3,3	6,3
Mattaponi River	3,3	3,3	3,3	6,3
Pamunkey River	3,3	3,3	3,3	6,3
North Landing	0	6	0	0
Elizabeth River	0	0	0	0
Piankatank River	6,6	6,6	6,6	6,6
Rappahannock River	3,3	2,3	2,3	6,3
Potomac River (MD)	6,3	6,3	6,3	6,6
Pocomoke River (MD)	6	6	6	6

TABLE 4.— Status of anadromous *Alosa* fish species in southeastern U.S. states in 1980 (Rulifson et al. 1982) and in 1992 (present study). 0 = never present; 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = no longer present; 6 = status unknown; 7 = stable but threatened. Dash indicates no response.

State and rivers	American shad		Alewife		Blueback herring		Hickory shad	
	1980	1992	1980	1992	1980	1992	1980	1992
North Carolina (20)								
North	-	2	3	3	3	3		
Pasquotank	-	2	3	3	3	3		
Little	-	2	3	3	3	3		
Perquimans	-	2	3	3	3	3		
Yeopim	-	2	3	3	3	3		
Chowan	3	2	3	3	3	3		
Meherrin	3	2	3	3	3	3		
Roanoke	3	2	3	3	3	3		
Cashie	-	2	3	3	3	3		
Scuppernong	-	2	3	3	3	3		
Alligator	-	2	3	3	3	3		
Tar-Pamlico	3	6	3	6	3	6		
Pungo	-	0	6	6	6	6		
Neuse	3	6	3	6	3	6		
Trent	3	0	3	6	3	6		
New	4	6	4	6	4	6		
Cape Fear	3	6	3	6	3	6		
North East Cape Fear	3	6	3	6	3	6		
Brunswick	-	6	-	6	-	6		
White Oak	6	0	-	6	6	6		
South Carolina (14)								
Waccamaw	2	2	0	0	2	2	2	2
Little Pee Dee	2	2	0	0	6	2	2	2
Great Pee Dee	2	2	0	0	2	2	2	2
Black	2	2	0	0	2	2	2	2
Santee	2	1	0	0	2	1	2	1
Cooper	2	2	0	0	2	2	2	2
Ashley	2	2	0	0	2	2	2	6
Edisto	3	3	0	0	2	6	2	6
Ashepoo	2	6	0	0	2	6	2	6
Combahee	2	6	0	0	2	6	2	6
Sampit	2	2	0	0	2	6	2	6
Salkehatchie	2	6	0	0	6	6	2	6
Savannah	2	2	0	0	2	6	2	6
Lynches	2	2	0	0	2	2	2	6
Georgia (7)								
Savannah	6	3	0	0	6	7	6	2
Ogeechee	3	3	0	0	6	7	6	2
Altamaha	6	3	0	0	6	7	6	2
Oconee	6	3	0	0	6	7	6	2
Satilla	3	2	0	0	6	7	6	2
Ocmulgee	6	2	0	0	6	7	6	2
St Marys	3	2	0	0	6	7	6	2
Florida (6)								
St. Marys	2	6	0	0	6	6	6	6
Nassau	2	6	0	0	6	6	6	6
St. Johns	3	6	0	0	3	6	3	6
Pellicer	3	6	0	0	6	6	6	6
Moultrie	0	0	0	0	0	0	0	0
Tomoka	3	6	0	0	3	6	3	6
Status changes for South Atlantic								
Increasing		1		0		1		1
Stable		5		0		0		0
From unknown to known		5		0		8		7
From known to unknown		13		6		16		13
Total changes		24		6		25		21

1977). Larvae occur throughout the lower portions of river systems, especially creeks and tributaries. In the summer, juveniles congregate in creeks and tributaries, then emigrate in the fall to overwintering areas in the sounds, bays, and deep estuarine areas. Adults overwinter in coastal ocean water. A south to north temporal progression of spawning season is observed, starting in January in Florida and late May to mid-July in Gulf of St. Lawrence rivers (Scott and Scott 1988).

In Atlantic Canada, approximately 81% of the reported rivers contain blueback herring runs, over half of which are along the Atlantic Coast of Nova Scotia (Table 1). Populations in Gulf of St. Lawrence streams are mostly stable, but the status of populations in streams draining into the Atlantic Ocean and Bay of Fundy are largely undocumented; the few remaining runs are in decline or threatened (Table 6).

Approximately 66% of the New England blueback herring runs are stable (primarily Connecticut), and nearly 12% are increasing due to habitat restoration and stocking programs for river herring (Table 6). Active stocking programs of pre-adult river herring, including blueback herring, are targeting 16 different river systems in Massachusetts, streams in Rhode Island, and the Cocheco River in New Hampshire.

In the mid-Atlantic states, about 28% of the reported blueback herring runs are in decline; an additional 27% are reported stable and 31% are undetermined (Table 6). New Jersey has the largest number of runs increasing in population. New York reported the continued expansion of blueback herring into the Mohawk River, which is the major tributary of the Hudson River above Troy Dam at Albany (K. Hattila, New York Dept. of Conservation, unpublished data). In 1992, the Conowingo fishlift collected 34,880 bluebacks for transport upstream. In addition, over 12,000 bluebacks were stocked above dams in the Susquehanna River, and 9,400 were given to Maryland for stocking in upper Chesapeake Bay tributaries (R. St. Pierre, unpublished data). In Virginia, blueback herring failed to negotiate the existing breaches of a dam at Richmond in 1992, but continued to successfully pass over Walker's Dam on the Chickahominy River.

In the south Atlantic states, only 15% of the blueback herring runs, exclusively in South Carolina, were thought to be stable; 24% are in decline (North Carolina) and 15% are low stable but threatened (Georgia; Table 6). Only the Santee River population in South Carolina was thought to be increasing (Table 4).

Hickory Shad

The closely related cousin of the American shad is the hickory shad. The species is relatively unstudied throughout its range. Mansueti (1962) reported that the species ranges from the Bay of Fundy to Florida, but Scott and Scott (1988) did not list its presence in the Canadian Maritimes. No hickory shad were observed in periodic sampling of commercial weirs in the inner Bay of Fundy in the mid-1980's (M. J. Dadswell, Acadia University, personal communication). Connecticut is the northernmost state to report the presence of hickory shad, but the status of the four runs was unknown (Table 7). The greatest population abundance is evidently centered from Delaware through South Carolina. Most life history aspects are poorly documented. The adhesive eggs are easily dislodged by currents, becoming semi-demersal in slow-moving water but buoyant in turbulent water. Larvae are found in fresh and brackish water tributaries. Juveniles frequent fresh and brackish water areas; lower estuaries and ocean nearshore areas are possibly used as nursery grounds. Adult oceanic distribution is unknown, but riverine distribution is similar to that of American shad. The spawning season is similar to that of shad, beginning in early March in southern latitudes (Marshall 1979) and continuing through May in northern latitudes.

The status of most hickory shad runs reported by state personnel was unknown. The Santee River population in South Carolina may be increasing (Table 4). Five populations in Virginia are declining, eight populations in Maryland and Delaware are threatened, and four in Maryland and Virginia are extirpated (Table 7). North Carolina may have the greatest abundance of hickory shad, but current status of these runs was not documented and thus was not reported.

Environmental Factors Influencing Anadromous *Alosa* Populations

In the Gulf of St. Lawrence, most of the *Alosa* populations are exploited commercially to some extent. A few rivers have fishway passage problems but the stocks seem to be able to sustain themselves within the available habitat. In general, the status of these fisheries appears to be fairly stable and not particularly threatened (G. Chaput, personal communication).

Along the Atlantic coast of Nova Scotia and the Bay of Fundy, populations of river herring have declined slightly or considerably over the past 20 years; the sharp decline in major runs throughout the region in the past three years was probably due to marine survival factors exacerbated by substantial fishing pressure. Otherwise, most runs are stable (B. Jessop, personal communication). In riverine habitats, 29 of the reported rivers have runs affected by dams and 19 rivers have inadequate fishway facilities (Tables 8 and 9). Declining stocks in three rivers may be attributed, in part, to poor control of water releases from impoundments. Chemical pollution and sewage may be a problem in the Annapolis River. The St. Croix River in Hants County, Nova Scotia, suffers from reduced spawning and nursery habitats (Table 9).

New England *Alosa* runs have been affected primarily by dams and inadequate fishways. At the present time, shad runs in Maine are almost nonexistent having been decimated very early in the late 1700's and early 1800's by the construction of impassable dams. A major run continued to exist in the estuarial complex of the Kennebec and Androscoggin rivers, including Merrymeeting Bay and its tributaries, although the run was probably reduced by over 50% by dams (T. Squiers, personal communication). This run declined in the 1930's due to severe pollution. Presently, only remnant stocks are present in Maine even though some rivers are now free of dams or existing dams have fish passages in them. All river systems in Maine now have sufficient water quality to support shad, but the major obstacle to shad restoration is suitable broodstock (T. Squiers, personal communication). River herring runs in Maine have declined since 1982. A combination of factors may be responsible: increased fishing mortality in the marine environment, increased natural predation in estuarine and marine environments, habitat degradation in nearshore waters, and increased obstruction to fish passage by the resurgence of beaver populations (T. Squiers, personal communication).

States in southern New England also have problems associated with dams, water releases, and inadequate fishways, but problems with water quality and habitat alterations are more prevalent (Tables 8 and 9). In Massachusetts, the major cause of *Alosa* stock decline was dams (15 of the rivers reported) blocking upstream passage, but pollution in the form of waste effluent from mills and factories killed spawning adults and destroyed spawning and nursery areas (Anonymous 1979). In 1935, the Massachusetts Division of Marine Fisheries initiated a program of fishway construction for alewives, which was expanded in 1967 to

TABLE 5.— Number of alewife runs of each stock status category along the east coast of North America. Stock status: 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = extirpated; 6 = unknown; 7 = low stable but threatened.

State or region	Rivers reported	Rivers with runs	Stock status 1	2	3	4	5	6	7
Gulf of St. Lawrence	14	13	0	11	0	0	0	2	0
Nova Scotia, Atlantic Coast	69	69	1	0	68	0	0	0	0
Bay of Fundy	62	59	0	0	53	1	0	5	0
Total Canada	145	141	1	11	121	1	0	7	0
Percent reporting		97.2	0.7	7.8	85.8	0.7	0	5.0	0
Maine	35	35	10	0	16	0	0	0	9
New Hampshire	8	8	3	2	1	0	0	2	
Massachusetts	15	15	4	7	2	1	0	1	
Connecticut	75	74	4	70	0	0	0	0	
Rhode Island	22	22	4	7	7	0	3	1	
Total New England	155	154	25	86	26	1	3	4	9
Percent reporting		99.4	16.2	55.8	16.9	0.6	1.9	2.6	5.8
New York	1	1	0	1	0	0	0	0	
New Jersey	115	104	3	7	0	0	0	94	
Delaware	13	12	0	6	3	0	0	3	
Maryland	25	22	1	11	8	0	1	1	
Pennsylvania	4	2	0	1	0	0	0	1	
Virginia	17	14	0	2	7	0	1	4	
Total Mid-Atlantic	175	155	4	28	18	0	2	103	0
Percent reporting		88.6	2.6	18.1	11.6	0	1.3	66.5	0
North Carolina	20	20	0	0	11	0	0	9	
South Carolina	14	0	0	0	0	0	0	0	
Georgia	7	0	0	0	0	0	0	0	
Florida	6	0	0	0	0	0	0	0	
Total South Atlantic	47	20	0	0	11	0	0	9	0
Percent reporting		42.6	0	0	55.0	0	0	45.0	0

TABLE 6.— Number of blueback herring runs of each stock status category along the east coast of North America. Stock status: 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = extirpated; 6 = unknown; 7 = low stable but threatened.

			Stock status						
State or region	Rivers reported	Rivers with runs	1	2	3	4	5	6	7
Gulf of St. Lawrence	14	13	0	11	0	0	0	2	0
Nova Scotia, Atlantic Coast	69	68	0	0	1	0	0	62	5
Bay of Fundy	62	36	0	0	5	1	0	28	2
Total Canada	145	117	0	11	6	1	0	92	7
Percent reporting		80.7	0	9.4	5.1	0.9	0	78.6	6.0
Maine	35	1	0	0	0	0	0	1	0
New Hampshire	8	8	3	2	1	0	0	2	
Massachusetts	15	15	2	3	2	1	0	7	
Connecticut	75	54	2	52	0	0	0	0	
Rhode Island	22	8	3	0	0	0	1	4	
Total New England	155	86	10	57	3	1	1	14	0
Percent reporting		55.5	11.6	66.3	3.5	1.2	1.2	16.3	0
New York	1	1	1	0	0	0	0	0	
New Jersey	115	24	5	3	0	0	0	16	
Delaware	13	12	0	6	3	0	0	3	
Maryland	25	22	1	6	12	0	1	2	
Pennsylvania	4	4	0	1	1	0	2	0	
Virginia	17	15	0	5	6	0	1	3	
Total Mid-Atlantic	175	78	7	21	22	0	4	24	0
Percent reporting		44.6	9.0	26.9	28.2	0	5.1	30.8	0
North Carolina	20	20	0	0	11	0	0	9	
South Carolina	14	14	1	7	0	0	0	6	
Georgia	7	7	0	0	0	0	0	0	7
Florida	6	5	0	0	0	0	0	5	
Total South Atlantic	47	46	1	7	11	0	0	20	7
Percent reporting		97.9	2.2	15.2	23.9	0	0	43.5	15.2

TABLE 7.— Number of hickory shad runs of each stock status category along the east coast of North America. Stock status: 1 = increasing; 2 = stable; 3 = declining; 4 = threatened; 5 = extirpated; 6 = unknown; 7 = low stable but threatened.

			Stock status						
State or region	Rivers reported	Rivers with runs	1	2	3	4	5	6	7
New Hampshire	8								
Massachusetts	15								
Connecticut	75	4	0	0	0	0	0	4	
Rhode Island	22								
Total New England	120	4	0	0	0	0	0	4	0
Percent reporting		3.3	0	0	0	0	0	100	0
New York	1	1	0	0	0	0	0	1	
New Jersey	115								
Delaware	13	13	0	0	0	1	0	12	
Maryland	25	15	0	0	0	6	3	5	1
Pennsylvania	4	3	0	0	0	0	0	3	
Virginia	17	12	0	2	5	0	1	4	
Total Mid-Atlantic	175	44	0	2	5	7	4	25	1
Percent reporting		25.1	0	4.5	11.4	15.9	9.1	56.8	2.3
North Carolina	20								
South Carolina	14	14	1	5	0	0	0	8	
Georgia	7	7	0	7	0	0	0	0	
Florida	6	5	0	0	0	0	0	5	
Total South Atlantic	47	26	1	12	0	0	0	13	0
Percent reporting		55.3	3.8	46.2	0	0	0	50.0	0

TABLE 8.— Potential physical and chemical factors involved in the decline of anadromous *Alosa* in rivers categorized by questionnaire respondees. Key to factors: C = channelization; DF = dredge and fill; B = bulkheading; D = dams; IW = industrial water intakes; ID = industrial discharge locations; RC = road construction; PF = other physical factors; AR = acid rain; CP = chemical pollution; TE = thermal effluents; T = turbidity; LO = low oxygen; SO = sewage outfalls; and CF = other chemical factors.

	Physical factors								Chemical factors						
Region and water body	C	DF	B	D	IW	ID	R	PF	AR	CP	TE	T	LO	SO	CF
Nova Scotia, Atlantic Coast															
East River Sheet Harbour				•											
West River Sheet Harbour				•											
Mushamush River				•											
LaHave River				•											
Petite Riviere				•											
Medway River				•											
Mersey River				•											
Roseway River				•											
Tusket River				•											
Nova Scotia, Fundy Coast															
Sissiboo River				•											
Bear River				•											
Annapolis River				•						•				•	•
Nictaux River				•											
Cornwallis River															•
Gaspereau River (Kings Co.)				•											
St. Croix River (Hants Co.)				•											
Kennetcook River				•											
Shubenacadie River				•											
Stewiacke River				•											
Salmon River (Colchester Co.)				•											
North River (Colchester Co.)				•											
Chiganois River				•											
Debert River				•											
Folly River				•											
Great Village River				•											
New Brunswick, Fundy Coast															
Petitcodiac River				•											
Irish River				•											
Saint John River				•											
Magaguadavic River				•											
St. Croix River (Charlotte Co.)				•											
Maine															
Androscoggin River				•						•					
Kennebec River				•						•					
St. George River				•											
Union River				•											
East Machias River				•											
Dennys River				•											
St. Croix River				•											
Penobscot River				•											
Mousam River				•											
Royal River				•											
Presumpscot River				•											
Sheepscot River				•											
Medomak River				•											
Ducktrap River				•											
Narraguagus River				•											
Pleasant River				•											
Orange River				•											
Pennamaquan River				•											
Saco River										•					
Nonesuch River										•					
Massachusetts															
Monument River				•											
Palmer River	•			•									•		
Indian Head River				•											

TABLE 8.— continued.

Region and water body	Physical factors								Chemical factors						
	C	DF	B	D	IW	ID	R	PF	AR	CP	TE	T	LO	SO	CF
Massachusetts—cont.															
South River				•											
Taunton River				•	•						•			•	
Charles River				•	•									•	
Merrimack River				•	•						•				
Runnins River				•											
Stoney Brook	•			•	•										
Agawam River				•	•										
Back River				•	•										
North River				•											
Jones River	•			•											
Town Brook				•											
Mattapoisett River				•											
Rhode Island															
Blackstone River				•	•	•							•	•	
Brickyard Pond Brook				•											
Woonasquatucket River	•	•		•	•	•	•						•	•	
Runnins River				•											
Pawcatuck River		•		•		•									
Connecticut															
Housatonic		•		•	•	•					•			•	
Connecticut		•			•	•					•			•	
Thames		•	•	•	•	•			•		•		•	•	
Maryland															
Potomac River	•	•	•	•		•	•	•1	•	•		•	•	•	•2
Patuxent River	•	•	•	•			•	•1	•	•		•	•	•	•2
South River								•1							•2
Severn River								•1							•2
Magothy River								•1							•2
Patapsco River				•				•1							•2
Bird River								•1							•2
Bush River								•1							•2
Gunpowder River								•1							•2
Susquehanna River				•		•		•1	•	•	•	•	•	•	•2
Northeast River				•				•1	•	•		•		•	•2
Bohemia River								•1							•2
Elk River				•				•1							•2
Sassafras River								•1							•2
Chester River	•	•	•				•	•1	•	•		•			•2
Choptank River	•	•	•				•	•1	•	•		•			•2
Nanticoke River	•	•	•				•	•1	•	•		•			•2
Wicomico River								•1							•2
Pocomoke River								•1							•2
Delaware															
Brandywine River			•	•	•	•	•	•3							
Christina River		•	•			•	•	•3		•		•			
Appoquinimink River												•		•	
Blackbird River												•			
Smyrna River				•								•			
Leipsic River				•								•			
St. James River				•								•			
Murderkill River				•								•	•	•	
Mispillion River	•			•								•			
Broadkill River	•			•								•			
Cedar Creek	•														
Indian River	•		•	•	•			•3					•	•	
Nanticoke River	•		•					•3	•	•					
Virginia															
Meherrin River				•								•		•5	
Nottoway River				•				•4							
Blackwater River								•4					•		

TABLE 8.— continued.

Region and water body	Physical factors								Chemical factors						
	C	DF	B	D	IW	ID	R	PF	AR	CP	TE	T	LO	SO	CF
Virginia—cont.															
James River	•	•		•	•	•		•[4]		•	•	•		•	
Nansemond River				•											
Chickahominy River				•		•		•[4]							
Appomattox River				•											
Pagan River												•		•	
York River					•	•		•[4]		•	•		•	•	
Mattaponi River						•		•[4]			•				
Pamunkey River						•		•[4]			•				
Piankatank River								•[4]							
Rappahannock River				•				•[4]				•	•		
Potomac River (MD)				•											
North Carolina															
North River		•					•						•		
Pasquotank River		•					•						•		
Little River		•					•						•		
Perquimans River		•					•						•		
Yeopim River		•					•						•		
Chowan River		•			•	•	•			•		•	•		
Meherrin River		•		•			•						•		
Roanoke River		•		•	•	•	•			•		•	•		
Cashie River		•					•						•		
Scuppernong River	•	•					•						•		
Alligator River		•					•						•		
Tar-Pamlico River		•		•			•						•		
Pungo River		•					•						•		
Neuse River		•		•			•						•		
Trent River		•					•						•		
New River	•	•					•						•		
Cape Fear River		•		•			•						•		
N.E. Cape Fear River		•					•						•		
Brunswick River		•					•						•		
White Oak River	•	•					•						•		
South Carolina															
Waccamaw River				•											
Great Pee Dee River				•		•									
Santee River				•											
Cooper River						•				•					
Edisto River											•				
Sampit River						•				•					
Savannah River	•			•	•	•				•	•		•		
Georgia															
Savannah River		•		•	•	•							•		
Ogeechee River	•														
Altamaha River					•	•									
Oconee River				•			•								

[1]sedimentation
[2]non-point source pollution
[3]residential construction
[4]overfishing
[5]logjams

TABLE 9.— Potential habitat management practices involved in the decline of anadromous *Alosa* in rivers categorized by questionnaire respondees. Key to factors: IF = inadequate fishways; WR = water releases from dams; RW = reduced freshwater input to estuaries; RS = reduced spawning habitat; RN = reduced nursery habitat; FA = poor food availability; F = fishing on spawning area; WQ = poor water quality; and HM = other habitat management practices.

Region and water body	IF	WR	RW	RS	RN	FA	F	WQ	HM
Nova Scotia - Atlantic Coast									
East River Sheet Harbour	•								
West River Sheet Harbour	•								
Mushamush River	•								
Petite Riviere	•								
Medway River	•								
Mersey River	•								
Roseway River	•								
Nova Scotia - Fundy Coast									
Sissiboo River	•								
Bear River	•								
Lequille River	•								
Annapolis River	•								
Nictaux River	•	•							
Gaspereau River (Kings Co.)	•	•							
St. Croix River (Hants Co.)	•	•		•	•				
Great Village	•								
New Brunswick - Fundy Coast									
Petitcodiac River	•								
Saint John River	•								
Magaguadavic River	•								
St. Croix River (Charlotte Co.)	•								
Maine									
Medomak River	•			•					
New Hampshire									
Taylor River									•1
Massachusetts									
Monument River		•							
Palmer River	•	•					•		
Indian Head River		•							
South River		•							
Charles River	•	•						•	
Merrimack River		•							
Agawam River		•							
Back River		•							
Jones River	•	•							
Town Brook	•								
Rhode Island									
Blackstone River	•	•		•	•			•	
Brickyard Pond Brook	•	•							
Woonasquatucket River	•	•		•	•			•	
Runnins Rivers	•	•							
Princess Pond Brook	•	•					•		
Kickamuit River	•	•							
Easten Pond	•	•							
Hunts River	•	•							
Tunupus Pond	•	•							
Wesquage Pond Brook	•	•							

TABLE 9.— continued.

Region and water body	IF	WR	RW	RS	RN	FA	F	WQ	HM
Rhode Island— cont.									
Quicksand Pond	•	•							
Gilbert Stuart Brook		•							
Potter Pond Brook	•	•							
Charlestown Brook	•	•							
Pawcatuck River	•								
Connecticut									
Housatonic River	•	•		•	•				
Connecticut River	•	•							
Thames River	•	•		•	•				
Pennsylvania									
Susquehanna River	•								
Schuylkill River	•								
Lehigh River	•								
Maryland									
Potomac River				•	•			•	
Patuxent River	•			•	•			•	
Patapsco River				•	•				
Susquehanna River	•	•		•	•			•	
Northeast River				•	•			•	
Elk River				•					
Chester River				•	•			•	
Choptank River				•	•			•	
Nanticoke River				•	•			•	
Delaware									
Brandywine River	•			•	•				
Christina River				•	•			•	
Smyrna River				•	•				
Leipsic River				•			•		
St. James River	•			•	•				
Murderkill River				•	•		•		
Mispillion River	•		•	•	•			•	
Broadkill River							•		
Indian River				•	•			•	
Nanticoke River							•		
Virginia									
Meherrin River	•	•		•			•		•2
Nottoway River				•					•2
Blackwater River								•	•2
James River	•		•	•				•	•2
Nansemond River	•		•	•					•2
Chickahominy River			•	•			•		•2
Appomattox River	•	•		•					•2
Pagan River								•	
York River								•	
Mattaponi River								•	
Pamunkey River								•	
North Landing River			•	•					•2
Rappahannock River	•			•					
North Carolina									
North River				•	•				

TABLE 9.— continued.

Region and water body	IF	WR	RW	RS	RN	FA	F	WQ	HM
North Carolina— cont.									
Pasquotank River				•	•				
Little River				•	•				
Perquimans River				•	•				
Yeopim River				•	•				
Chowan River				•	•			•	
Meherrin River				•	•				
Roanoke River		•		•	•			•	
Cashie River				•	•				
Scuppernong River				•	•				
Alligator River				•	•				
Tar-Pamlico River			•	•	•				
Pungo River			•	•	•				
Neuse River		•		•	•				
Trent River				•	•				
New River				•	•				
Cape Fear River				•	•				
N.E. Cape Fear River				•	•				
Brunswick River				•	•				
White Oak River				•	•				
South Carolina									
Waccamaw River									
Great Pee Dee River	•	•		•	•				
Santee River	•	•		•	•			•	
Cooper River	•	•	•					•	
Sampit River								•	
Savannah River	•	•		•	•			•	
Georgia									
Savannah River	•	•		•	•		•	•	•[3]
Ogeechee River									•[3]
Altamaha River		•							•[3]
Oconee River									•[3]
Satilla River									•[3]
Ocmulgee River									•[3]
St. Marys River									•[3]

[1]overfishing or poaching
[2]water withdrawal (drinking water)
[3]coastal ditching

include shad (Anonymous 1979). Additional problems in Massachusetts, Rhode Island, and Connecticut include channelization (4 rivers), dredge and fill (5), and industrial water intakes (11) and discharges (6). Water quality affected by thermal effluents (5 rivers), low oxygen (4), and sewage (7) is also a factor. Inadequate fishways (21 rivers) and poor control over water release schedules (26 rivers) are other problems associated with dams (Tables 8 and 9).

Within the New York Harbor and Staten Island area of New York and New Jersey, Durkas (1992) reported that a number of tributaries to coastal watersheds contain impediments to anadromous *Alosa*. In the Sandy Hook Bay region (tributaries of the Shrewsbury and Navesink rivers), problems include dams and spillways (6), culverts (3), concrete river beds (1), and poor water quality (2). In the Raritan Bay area (tributaries of Keyport Harbor, Cheesequake Creek, Raritan River, and South Staten Island), problems included dams and spillways (10), tide gates (1), culverts (3), and poor water quality (7). In the Arthur Kill drainage area of New Jersey and New York (Rahway and Elizabeth rivers, Morses Creek, and West Staten Island), anadromous fish passage is impeded by dams and spillways (6), tide gates (1), culverts (1), concrete river beds (3), and poor water quality (5). In Newark Bay (Passaic and Hackensack rivers and their tributaries), tide gates (4) or earthen berms (4) block access to creeks. Other access problems are caused by dams and spillways (4), concrete river beds (1), and poor water quality (5).

Anadromous *Alosa* runs in the mid-Atlantic and southeastern states are affected by numerous factors, many of which are related to physical disturbances of habitats. Problems exist with sedimentation (19 rivers), turbidity (19), and non-point source pollution (19). These activities include, but are not limited to: channelization, dredge and fill, and road and residential construction (Table 8). In Virginia, anadromous *Alosa* populations also are affected by water withdrawal (8 of the reported rivers). In the Albemarle and Pamlico sounds of North Carolina, obstructions to fish passage were catalogued by Collier and Odum (1989). A total of 27 obstructions were located: 18 dams, 4 storm gates on canals, 2 highway culverts, 2 vegetational blockages, and 1 navigational lock. An additional 30 impediments were identified on stream reaches where anadromous fish usage is suspected but not confirmed. These obstructions included 21 highway culverts, 8 dams, and 1 beaver dam.

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The Anadromous *Alosa* Symposium in Retrospect: What Have We Learned?

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There are four species of anadromous *Alosa* that occur along the east coast of North America: alewife *Alosa pseudoharengus*, blueback herring *A. aestivalis*, American shad *A. sapidissima*, and hickory shad *A. mediocris*. Two additional *Alosa* species, the Alabama shad *A. alabamae*, and the skipjack herring *A. chrysochloris*, occur along the Gulf of Mexico coast but were only briefly discussed in the symposium. American shad, alewife, and blueback herring have received the greatest scientific investigation because they are of importance in commercial and recreational fisheries and thus are of primary management interest. The agencies that are charged with managing the fishery resource have directed their energies toward these more politically-visible species which has left the hickory shad as relatively unknown. This emphasis was evident in the symposium as hickory shad were barely mentioned and were not included in any major way in most of the studies that were presented.

Anadromous *Alosa* were a valuable source of protein to native Americans as well as the early European colonists. The effect of increased human activities on *Alosa* became apparent as early as 1623 when the first legislation protecting anadromous fish was passed. Then, as now, political maneuvering reduced the effectiveness of these conservation measures. Construction of dams in Maine blocked the upstream migration of salmon (and presumably *Alosa*) and by 1739, fighting had broken out over the fishery resource between native Americans and the European colonists. Human activity continued to reshape the land and rivers and the fishery continued to decline through the 1700's and 1800's. More legislation was passed to protect the remaining stocks but enforcement of these fishery laws was weak, and in some areas, unknown. In the more recent past, legislation intended for other fish species has helped to conserve the *Alosa* stocks. There is now a greater awareness on the part of agencies and politicians of the value of the *Alosa* resource and the benefits that can be accrued by restoring the once plentiful stocks.

The most singular idea to emerge from the symposium was of declining fishery stocks and that it was based more on perception than on scientific evidence. The present level of monitoring of fishing pressure and effort is inadequate to describe the true nature of the *Alosa* stocks, particularly for hickory shad. Nearly all of the *Alosa* have migratory phases that take them through the jurisdiction of several states and provinces, yet not all of these areas have the same harvest regulations - a fish may face several types of harvest gear before it reaches its spawning stream where it may or may not be protected. One reason for this apparent deficiency is that some stocks appear to be abundant and thus do not warrant closer study, but the genetic composition of all the stocks remains uncertain. We do not know which "stocks" are truly in danger, only that many apparent populations are in serious decline. Much of the results presented in the symposium indicated that *Alosa* populations continue to decline, even in areas were there is some measure of protection. This would indicate that protection in one area may not be sufficient to restore or stabilize the *Alosa* population. In addition, new regulations in one area may increase the fishing pressure in other, less regulated areas.

There were many examples of technological endeavors to reduce the influence that past mistakes have had on the migration and reproductive success of *Alosa*. Dams and similar structures are the primary barriers to restoring the *Alosa* stocks. Technological advances in fishways and transport systems give some hope that the problems with stream blockages can be overcome but only at great cost. Many previous attempts in various streams and rivers ended in failure because information on the behavior of *Alosa* was lacking; we are still a long way from being able to credibly predict which fish passage structures will be successful in many situations. The outright removal of dams and other barriers eliminates the need for more technological solutions.The improvement in water quality over the past 20 years has substantially improved the chances that native *Alosa* populations can return to their natal streams; however, in many areas the population is now so low that stock recovery may not be possible.

Repopulation of certain waterways has been attempted by transplanting *Alosa* from other areas. In some cases this appears to be successful but in many others the transplanted fish failed to return to the streams or to reproduce. The introduction of new strains into native populations brings with it certain problems that may create a more difficult environment for both introduced fish and the native populations. Mixing of genetic material may create fish that are ill-suited to the current environmental conditions and may not be able to adapt rapidly enough in the face of future changes.

The future of the *Alosa* stocks depends on what is done now. There is a need for a more coordinated management plan in all the coastal states. Each river system must be viewed as a part of the whole *Alosa* habitat. One "stock" that may be abundant in one area may in truth be a declining stock elsewhere. Any management strategy must account for the migratory behavior of *Alosa*. Until we know which stocks are distinct (if any are), we should manage the impact that humans have in a conservative manner in favor of the fish. We need more information about the basic biology of all *Alosa*, and in particular hickory shad, before we embrace technological solutions. Fish passage studies have shown that it is possible for *Alosa* and other genera to bypass certain obstructions if the passages are built correctly. The problems for fish passage seem similar from one area to another but a solution for one area may not be a solution elsewhere and may actually hasten the decline of the population.

The Endangered Species Act is apparently not an option for restoring *Alosa* populations at the present time. It may be a blessing that we do not need the Act as yet but we cannot afford to squander our opportunities. We have the time now to acquire the basic biological knowledge of the *Alosa* populations but is there the political will? Do we need conclusive proof of a declining resource or is it enough to have strong associations with probable causes for the decline? If we wait until we have scientific certainty and the stock is then beyond restoration, our certainty will be of little consequence.

Abstracts

The Symposium conveners encouraged the presentation of ongoing research as well as finished papers. The following abstracts are from those papers that were presented but were not published as part of the Symposium.

Migratory Patterns and Exploitation of American Shad in the Nearshore Ocean Waters of Southeastern North Carolina

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A tagging study of American shad *Alosa sapidissima* was conducted in the nearshore ocean waters of southeastern North Carolina from January through April, 1989, and from December, 1989, through May, 1990. The objectives were to determine the migratory patterns of spawning anadromous American shad in those waters and to ascertain if the nearshore fishery was intercepting the shad that spawn in the states farther south. A total of 301 fish was tagged with Floy FT-1 dart tags. Fifty-seven tags were returned and all but three of these had been recaptured south of the tagging site: 42 (74%) from North Carolina, 14 (24%) from South Carolina, and 1 (2%) from Georgia. Bottom water temperature at which shad were recaptured ranged from 8.6° to19.9°C with most fish recaptured at 13.0°C. This study shows that American shad captured in the nearshore ocean waters exhibited a pronounced southerly migration pattern and supports the hypothesis that South Atlantic shad migrate within a narrow coastal corridor between the coast and the Gulf Stream. I estimated an exploitation rate of 18.9% and confirmed that the nearshore ocean fishery intercepts shad that migrate to more southerly states. The results indicate that there is a need for regulatory restrictions on the gill net fishery in the nearshore ocean waters in southeastern North Carolina.

Observations of Intra-system Movements, Homing, and Long Distance Migrations of Blueback Herring

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Between 1971 and 1990, over 200,000 adult blueback herring *Alosa aestivalis* were tagged and released in the Santee River, South Carolina, as part of a long-term population study. Recaptures from within the system have given indications of delay time involved in fish passage and the residence time of fish passed into the lakes and fish recaptured in the river. Returns of tagged fish to the Santee River, after one or more years of absence, has provided further evidence of homing in blueback herring. Tags returned from outside the Santee River system, from South Carolina to the Bay of Fundy, Canada, provided data on the timing and routes of ocean migrations.

Habitat Relationships for Spawning Alewives and Blueback Herring in a Virginia Stream

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Alewife *Alosa pseudoharengus* and blueback herring *A. aestivalis* eggs, larvae, juveniles, and spawning adults were sampled at three sites in Occupacia Creek, a tributary of the Rappahannock River in Essex County, Virginia. Samples were taken at dawn, midday, dusk, and midnight on a five day, rotating basis from February to May 1992. Alewives spawned from February 24 to April 15 at water temperatures of 9.5° to 19.6°C; blueback herring spawned from April 13 to May 13 at water temperatures of 13.8° to 21.5°C. Spawning of both species occurred throughout the diel cycle. Spawning and yolk-sac larvae of both species occurred only at the upstream site, 16.4 km from the creek mouth. Prejuveniles were found at the midstream site (9.1 km from the creek mouth) and the downstream site (5 km from the creek mouth). Our results indicated that upstream areas provided valuable spawning sites for river herring whereas downstream areas provided nursery habitat.

Possible Ecological Roles of Adult Blueback Herring *Alosa aestivalis* in Tidal Freshwater

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Most ecological studies of anadromous *Alosa* in tidal freshwater focus on young-of-year individuals and assume that spawning or post-spawning adults have no ecological role during freshwater residency. However, a growing body of evidence suggests that this assumption may not be valid. Preliminary findings suggest that excretion by large spawning aggregations of blueback herring *A. aestivalis* in small tidal and nontidal streams can increase ambient ammonia (NH4+) concentrations to levels that are known to cause stress responses in a variety of fish and aquatic macroinvertebrate taxa. As a result, adult *Alosa* may substantially affect the resident community in freshwater systems. In addition, because of significant post-spawn mortality, anadromous *Alosa* may function as vectors of energy and nutrients of marine origin. In a test of this hypothesis, retention and processing rates were measured of blueback herring carcasses experimentally introduced into a freshwater stream. Export rates of carcasses were low, averaging 8 and 17 m/d for nontidal and tidal stream sections. Rates of processing by nonmicrobial agents, including vertebrate aquatic scavengers and a wide range of benthic macroinvertebrate taxa, were rapid for introduced carcasses. These findings, together with preliminary stable isotope analyses, suggested that post-spawn carcasses of *Alosa* significantly subsidized annual energy and nutrient budgets of tidal freshwater systems, prior to the recent decline in anadromous *Alosa* abundance.

Relations Between the Abundance of Juvenile Alewives and Blueback Herring and Spawning Escapement, Population Fecundity and Environmental Variables in the Mactaquac Dam Headpond, Saint John River, New Brunswick

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Indices of juvenile abundance or density have been used to forecast trends in adult recruitment and stock abundance for both marine and anadromous fishes. The usefulness of an index or abundance depends on its accuracy and precision of estimation and its validity or strength of relationship with recruitment or future stock size. A positive, significant correlation between juvenile abundance and adult recruitment or year-class size forms the latter part of a stock recruitment relation, the former part being the relation between escapement and juvenile abundance. Validity of a juvenile abundance index is often assumed because of the difficulty of acquiring a data time series of sufficient length or contrast, particularly for anadromous species.

This study examines a) the relation between the spawning escapements and population fecundity of alewives *Alosa pseudoharengus* and blueback herring *A. aestivalis* and a seasonal maximal index of juvenile abundance in relation to seasonal water temperature and discharge; b) density effects on juvenile lengths and weights; and c) species interactions. A preliminary examination is also made of juvenile density in relation to virgin spawner year-class abundance.

Preliminary results indicate a) an increase in juvenile density with increasing adult escapement and population fecundity ($P < 0.1$) for alewives but not for blueback herring ($P > 0.5$); b) a decrease in mean length and weight of juvenile alewives ($P < 0.02$) but not of blueback herring, with increasing juvenile density; and c) possible interaction between juvenile alewife density and blueback herring density and growth.

Growing Shad on the Move: The Ecology of Juvenile American Shad Out-migration from Natal Rivers

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An important phase in the life history of American shad *Alosa sapidissima* is the movement from natal rivers into coastal marine areas, where further growth occurs. Out-migration is often thought to be triggered by the onset of cooler weather in the fall but evidence suggests that the process may begin as early as mid-summer. When viewed as a life history strategy, one may examine a variety of factors that affect the timing of this habitat switch. Field, experimental, and modelling approaches were combined to assess the relative importance of predation risk, food availability, and thermal constraints on the out-migration of American shad populations from the Hudson River.

Recent Trends in Anadromous *Alosa* Migration to District of Columbia Waters

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The anadromous *Alosa* are important species in the Potomac and Anacostia rivers in the District of Columbia. There has been a considerable decline in the number and size of these species in this area, except for alewife *A. pseudoharengus*. Adult hickory shad *A. mediocris* were not collected in 1990 or 1991 and only one hickory shad and one blueback herring *A. aestivalis* was collected in 1992. A management policy has been formulated for *Alosa* in the District of Columbia waters.

American Shad Restoration in the James River, Virginia

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American shad *Alosa sapidissima* play a potentially important role in the economics and ecology of Atlantic coastal waters. However, American shad abundance has declined dramatically in Virginia: the 1987 catch in the James River represented less than 1% of the historical landings. As a result, the James River has been the focus of an American shad restoration and research effort that started with the breaching of two low-head dams in 1989 near Richmond. This effort involved a number of state and federal agencies including the Virginia Department of Game and Inland Fisheries, the Council on the Environment, and Virginia Commonwealth University. Research included population monitoring at the Fall Line, fish passage studies, egg procurement for hatchery production, and evaluation of biotic interactions. Since 1989, annual spring electrofishing in the Richmond area collected few American shad (n < 20). In 1992, greater numbers (n = 205) were collected by electrofishing in the Bosher's Dam tailrace, approximately 5 km west of Richmond. Gametes from these American shad and 29 females from the Chickahominy River were combined to produce an estimated 100,000 fry for stocking in 1992. Predation of American shad fry, determined by predator gut analysis, was substantial immediately after stocking. Redbreast sunfish *Lepomis auritus* and smallmouth bass *Micropterus dolomieu* were the dominant predators.

Role of Philadelphia Electric Company's Fish Passage Facilities in Restoration of Anadromous Fishes to the Susquehanna River

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A major goal of the restoration program for the Susquehanna River is to provide migrating anadromous fishes (American shad *Alosa sapidissima*, river herrings *A. aestivalis* and *A. pseudoharengus*, hickory shad *A. mediocris*, and white perch *Morone americana*) with access to the ancestral spawning grounds throughout the upper reaches of the river. Philadelphia Electric Company expanded its fish passage facilities at the Conowingo Hydroelectric Station and began operation of the Conowingo East Fish Passage Facility in the spring of 1991. This new facility complements a fish lift which was constructed on the west side of the powerhouse in 1972. The East Fish Passage Facility employs the latest technology to attract, collect, and pass American shad upstream of the dam. Anadromous fishes can be transported by truck or allowed direct access to the upstream impoundment from this facility. The number of American shad passed has increased from an average of 100 per year in the 1970's to over 25,000 per year at present. Two years of operating experience indicates that the existing fish passage facilities contribute significantly to the restoration efforts and are capable of attracting large numbers of the target species. It appears that no major modifications to the new fish passage facility will be needed in the foreseeable future.

Effect of Illumination Intensity on the Water Velocity Preference of Adult American Shad

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An understanding of daily activity cycles and the effect of light intensity on the rheotropic response of migrating fish can be important to the successful design and operation of fish passage facilities. This is particularly important when passing diurnal migrants that cannot ascend a long fishway within one daylight period. We studied the water velocities preferred by pre-spawning adult American shad *Alosa sapidissima* during the diel cycle using U - shaped channels with a flow gradient of 23-37 cm/s at one end and 6-10 cm/s at the other end. Test conditions were divided between natural illumination and artificial illumination. Peak use of fast flows occurred during the day (dawn to dusk) but there was some use of fast flows at night. Artificial light greatly enhanced the use of fast water with 58% of fish locations in fast water at night. Less than 300 lux at night was needed to double the fish's use of fast water. The choice of water velocity was mediated by illumination intensity so that fish used the fastest flows during the day but not at night. Our results provide the probable cause for the poor nocturnal passage observed in fish ladders and the reasons for the departure of migrants at dusk from fast flow areas of fishway entrances. The results also indicate that artificial illumination can be used to prevent nocturnal drop-back in fishways by eliciting the daytime rheotropic response in fish and stimulating them to hold their position.

Chesapeake Bay Interstate Fish Passage - Restoration Program

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The migratory species of the 260 fish species found in the Chesapeake Bay drainage, have comprised the majority of catches and monetary values by sport and commercial fishermen. These species include the anadromous striped bass *Morone saxatilis*, river herring *Alosa aestivalis* and *A. pseudoharengus* and shad *A. sapidissima*, and the semi-anadromous white perch *Morone americanus* and yellow perch *Perca flavescens*. Landings of these once plentiful fish species are at their lowest level in history with recent Baywide declines of 80 to 90 percent. Experts agree that the reasons for the decline include pollution, overfishing, and hundreds of barriers to migration that have prevented access to spawning and nursery habitat. The signatories of the Chesapeake Bay Agreement included a fish passage commitment in their 1987 'Save the Bay' initiative for the restoration of migratory species. Dams, highway culverts, and various other obstructions, some of which have blocked upstream fish migration since the Industrial Revolution, are being retrofitted with fish passage facilities. Migratory fish are being imprinted to the habitat upstream of blockages that are slated for removal or modification and biomonitoring surveys are underway. Interstate participants in the fish passage program include Maryland, Virginia, Pennsylvania, and the District of Columbia. Maryland has been particularly active in its commitment: fourteen fish passages have been completed, four others are under construction, and many others are being planned.

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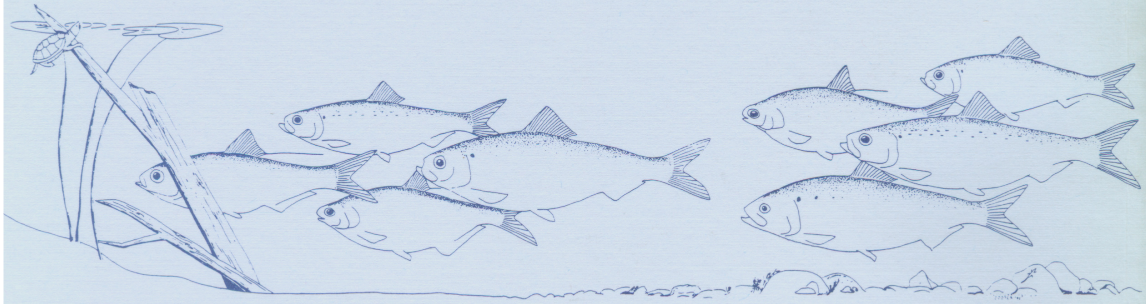

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