FINAL REPORT

# ANALYSIS OF IMPEDIMENTS TO SPAWNING MIGRATIONS OF ANADROMOUS FISHES IN VIRGINIA RIVERS


Prepared by:

John M. Mudre
John J. Ney
Richard J. Neves

Department of Fisheries and Wildlife Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061



Sponsored by:

Virginia Highway Research Council
Virginia Department of Highways and Transportation

August, 1985

VHTRC 86-R11

ABSTRACT

The historic and present ranges of anadromous alosids and striped bass were determined for three of Virginia's rivers. American shad, blueback herring, and alewives migrated to at least Remington (river mile 188) on the Rappahannock River. They ascended the entire length of the York River, reaching at least Milford on the Mattaponi and the entire length of the Pamunkey. The alosids traversed the full length of the James River, reaching above Clifton Forge and Covington. Although striped bass were historically caught in the James as far upstream as Balcony Falls (near Glasgow) and probably as far upstream as shad on the other rivers, it is doubtful that they ever spawned above the fall line on any river. Present ranges for all species are Fredericksburg (Embrey Dam) on the Rappahannock, unchanged on the York, and Richmond (Bosher Dam) on the James.

One dam on the Rappahannock River and twelve dams on the James River were identified as actual or potential barriers to the upstream spawning migrations of Virginia's anadromous fishes. Elimination of these barriers by breaching, in the case of unused facilities, or by the construction of fish

passage facilities would result in the restoration of 47 miles of mainstem river (a 30% increase) on the Rappahannock and 226 miles (a 200% increase) on the James. Water quality was found not to be sufficiently degraded on these rivers to impede spawning migrations of anadromous fish.

The dams identified on the James and Rappahannock Rivers were investigated to assess the feasibility of eliminating them as barriers to upstream migration of anadromous fish, and to project a timetable estimating the probable dates of accomplishment. The Embrey Dam at Fredericksburg on the Rappahannock may soon be modified to permit fish passage. On the James, five dams at Richmond are currently being considered for passage modifications; access to an additional 139 miles of the James appears likely by the early 1990s. Access to the remainder of the upper James River is blocked by a series of seven hydropower dams in the Lynchburg area. Passage around this series of barriers cannot plausibly be anticipated for at least 30 years.

Biological requirements for passage of the anadromous species, and a synthesis of the state of knowledge of fish passage facilities and fish passage through culverts are included in this report.

# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## INTRODUCTION

Virginia's anadromous fishes have historically provided a rich resource for the Commonwealth. American shad (*Alosa sapidissima*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), and striped bass (*Morone saxatilis*) ascend Virginia's tidal rivers each spring to spawn. These species constitute commercial and (historically) subsistance food fisheries, and a sport fishery of substantial economic significance. However, harvest of these species in Virginia waters has now declined to record low levels, and the negative trend in catch appears to be continuing (Atran et al. 1983).

Probable causes of the diminishment of Virginia's anadromous fishes are multiple and interactive. These include overfishing, pollution of the Chesapeake Bay, and the elimination of access to upstream spawning sites. Concern for the resource has prompted actions to remedy all these problems. Stricter fishing regulations (most notably for striped bass) have been implemented and/or proposed, and multi-state efforts to restore the Bay are underway. The Virginia Legislature has authorized a feasibility study of

fish passage devices on the James River to restore access for these species to their historical spawning grounds as much as 100 river miles above Richmond. The legislation resulted not only from the desire to restore the anadromous fish populations to their former levels, but also to provide fishing opportunities for inland anglers.

The initiative to facilitate upstream passage of anadromous fish is a popular one, fueled both by the sorry condition of the present fisheries, and recent successes in the New England states in restoring spawning runs with passage devices (McConnell and Strand 1981; Moffitt et al. 1982). While the early focus has been on the James River, it is reasonable to assume that interest will spread to the other major tidal rivers in Virginia, the York, Rappahannock, and their tributaries, particularly if the James River effort is successful.

Assessment of the potential for restoring anadromous fish to their former spawning grounds in Virginia must address sequential questions: 1) what is the present upstream limit of these fishes' migrations; 2) what impedes them from going further; 3) how far upstream would they go if these impediments were eliminated; and 4) is it feasible to remove the impediments?

Studies of impediments to upstream passage of fish have usually focused on physical barriers, but impediments may also be chemical (e.g. pollution) or thermal in nature. While most efforts to restore fish access have concentrated on dams (e.g. fish ladders or lifts), it is also recognized that highway structures in/across streams may potentially constitute impediments. Culverts which restrict stream width and increase velocity have been observed to obstruct upstream fish movement in Canada (Jones et al. 1974) and the western U.S. (MacPhee and Watts 1976). Highway design/construction could also potentially affect fish movement by steepening gradient, increasing turbidity, changing instream habitat, or destroying migrational cues. However, knowledge of these latter impacts is scattered and incomplete.

This study was designed to provide an evaluation of the probable occurrence and significance of highway impediments to the migration of anadromous fish in Virginia, now and in the future. This report details the findings of Phase 1 of this study. The objectives of Phase 1 were to: 1) determine the present and historic extent of the upstream migration of American shad, alewife, blueback herring, and striped bass in the Rappahannock, York, and James Rivers; 2) identify existing natural and manmade impediments to the upstream

migration on these rivers; 3) assess the feasibility (probability) of eliminating of these barriers; and 4) develop a state of knowledge synthesis of factors which limit instream migration of these species. This report consists of four sections, each addressing one of the four objectives.

## Historic Perspective

> In the spring of the year, herrings come up in such abundance into their brooks and fords to spawn that it is almost impossible to ride through without treading on them... Besides these herrings, there come up likewise into the freshes from the sea multitudes of shad, rock, sturgeon and some few lampreys... (Beverly 1705)

> Herring are not as large as the European ones... When they spawn, all streams and waters are completely filled with them, and one might believe, when he sees such terrible amounts of them, that there was as great as supply of herring as there is water. In a word, it is unbelievable, indeed, indescribable, as also incomprehensible, what quantity is found there. One must behold oneself. (Byrd 1737)

The above quotations are typical of many describing the great abundance of anadromous fishes present in Virginia's river systems during the Colonial period. These fishes were important to the colonists both as food and as fertilizer for their crops. As the Colonial period progressed however, man began using these rivers as more than just a source of

fish and as a natural means of transportation. He began to "improve" them.

The most significant of these "improvements" with respect to anadromous fishes was the construction of numerous dams across these rivers. These early dams were constructed for two purposes: to create millponds to drive the mills; and more significantly, to allow the construction of canal systems that would allow navigation to previously unreachable inland cities.

The effect of these dams on the anadromous fish populations in these rivers was so dramatic that it was soon recognized and lamented. Thoreau in his "Week on the Concord and Merrimac Rivers" (1837 p. 37) wrote:

> Poor shad! Where is thy redress? When nature gave thee instinct, gave she thee the heart to bear thy fate? Still wandering the sea in thy scaly armor to inquire humbly at the mouths of rivers if man has perchance left them free for thee to enter... Who hears the fishes when they cry?

Apparently no one. Dam construction continued unabated: by 1875 there were 21 dams on the James between Richmond and Buchanan (Virginia Fish Commission 1875). Despite early laws designed to ensure the passage of fish upstream of the dams (summarized by Atran et al. 1983), anadromous fish populations continued to decline to the present levels.

## Report Sequence

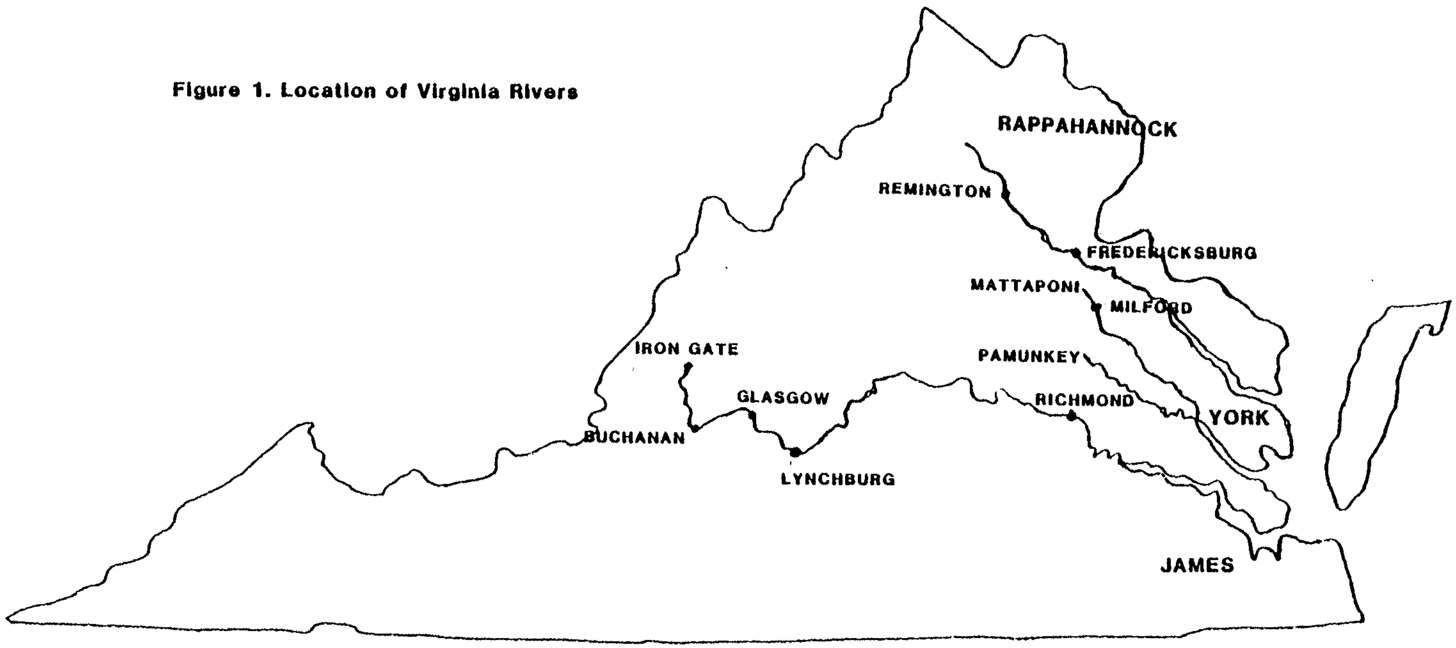
### Range

The first section of this report delineates the present and historic ranges of the American shad, river herring (blueback herring and alewife), and striped bass in the main stems of Virginia's three main river systems. Specifically these include: the Rappahannock River to its source; the York River, including its two main tributaries the Mattaponi and the Pamunkey; and the James River to Iron Gate, where it is formed by the union of the Cowpasture and Jackson Rivers (Figure 1).

### Impediments

This section identifies the chemical (pollution), thermal, and physical barriers (i.e. dams) to the upstream migrations of these anadromous fishes starting with the dam that forms the present upstream limit of migration, and proceeding upstream until the historical limits of migration are reached. This report covers only the mainstems of these rivers, and does not address their various tributaries. It should be noted though, that restoration of mainstem river to the fishes' ranges almost in every case also results in the restoration of access to tributaries as well.

Figure 1. Location of Virginia Rivers



Feasibility

The purpose of this section is to assess the feasibility (and probability) of elimination of both physical structures and potential water quality problems previously identified as barriers to upstream movement of anadromous fishes on these mainstem rivers. As part of this analysis, a timetable for passage past present barriers will be projected, based on best available information at this time.

It must be recognized that this exercise represents only a best estimate. Uncertainties regarding the economic and political factors which ultimately dictate whether and when barriers will be overcome are such that the assessments presented here must be interpreted with caution. It is still possible, for example, that no barriers will be successfully eliminated on any Virginia river. However, we utilized present legal, political, economic information and personal communications to present the most likely scenarios that can be developed at this time.

Literature Synthesis

The last section covers the abilities of fishes to transcend man-made barriers such as dams, which have played a very important role in limiting the spawning migrations of anadromous fishes. Depending on the nature and location of

these barriers, anadromous fish runs in these rivers may be diminished or curtailed. Polluted water can also effectively block the runs of these fishes.

Man has realized the deleterious effects these barriers have had on anadromous fish populations: the need for fish passage facilities at dams has been recognized since the late 1700's. Requirements for the improvement of water quality have been incorporated into shad restoration projects.

The success of these restoration programs is dependent on a knowledge of the biological capabilities of the species in question to surmount barriers, and also the ability to put this knowledge to work in the construction of fish passage facilities or water quality improvement plans. This section addresses both of these topics, and includes a discussion of what is known relative to the passage of these species through culverts.

# METHODS

## Range Determinations

Historic ranges were determined by a review of accounts of Colonial fisheries and the early reports of the Virginia and U.S. Fish Commissions. Archives in the Virginia Tech library were searched for references to early fisheries and distributions of anadromous species, and additional information was provided by the library of the Virginia Institute of Marine Science (VIMS). Two computer-assisted literature searches were conducted to identify additional references.

Present ranges, and to a lesser extent historic ranges, were further defined through communication with knowledgeable personnel of the Virginia Commission of Game and Inland Fisheries (VCGIF), VIMS, Virginia Electric Power Company (VEPCo), the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS).

In several instances , it proved impossible to set a definitive upstream boundary on the historic range. Most records listed the occurrence of a species at a particular site without noting whether they migrated further upstream.

Limits derived from these records must be considered conservative.

River mileages to the various locations were taken from a variety of sources and/or estimated from USGS topographic maps and should be considered approximate.

## Impediments

### Water Quality

Potential water quality impediments were assessed through consultation with the State Water Control Board (SWCB), which has the authority to monitor and interpret water quality, and also to promulgate and enforce water quality regulations for surface waters in Virginia.

### Dams

Impediments were identified after researching pertinent literature including Carter (1974), Corbett (1977), Federal Energy Regulatory Commission (1981), Rockfish Corporation (1981), and Atran et al. (1983). USGS topographic maps were also inspected to identify any structures that may not have been listed in the literature. Personal communication with individuals familiar with specific areas was used to update written information. These persons included: Mr. Bruce Williams, U.S. Army Corps of Engineers, Norfolk; Mr. Clay

Bernick, Virginia Marine Resources Commission; Mr. Jerry Fouse, Virginia Commission of Game and Inland Fisheries; Mr. Glen Kinzer, U.S. Fish and Wildlife Service, Annapolis; and Dr. Ed Christoffers, National Marine Fisheries Service.

James River mileages are official U.S. Army Corp of Engineers mileages. River mileages on the Rappahannock River are estimated from USGS maps.

## Feasibility

This assessment is based on information received from other parties. Dam owners/operators were contacted to determine their plans for future operation of their facilities and their positions on modifying their structures to permit fish passage. The Federal Energy Regulatory Commission (FERC), which has licensing authority for hydropower dams, responded to requests for information, as did the Virginia Commission of Game and Inland Fisheries (VCGIF), which is responsible for anadromous fish restoration in Virginia rivers, and the U.S. Fish and Wildlife Service, which has a strong committment to anadromous fish restoration.

## Literature Synthesis

An exhaustive review of the literature was made to identify research that has been conducted relative to the upstream spawning migrations of striped bass, American shad, blueback herring, and alewives, with special attention to their ability or success in using fish passage facilities at dams. While many studies addressing fish passage problems have been conducted on Pacific salmon and trout, and may have some relevance to the species of interest, they are not included herein.

A fact-finding trip was made to Massachusetts to confer with experts on the passage requirements and abilities of these fishes, and to examine the libraries at the University of Massachusetts to identify relevant unpublished theses and dissertations therein. This was important because most of the knowledge regarding the passage of these species is unpublished, and resides in the files and minds of the people who conducted the research. Persons contacted included: Dr. Boyd Kynard, Assistant Unit Leader, Massachusetts Cooperative Fishery Research Unit; Mr. Steve Rideout, United States Fish and Wildlife Service; and Mr. Buzzy DiCarlo, Massachusetts Division of Marine Fisheries.

# RESULTS AND DISCUSSION

## Range Determinations

### Rappahannock River

Walburg and Nichols (1967), quoting Stevenson (1899), state that the historic limit of the shad run was Falmouth Falls, just upstream of Fredericksburg, and 155 mi from the river mouth. However, careful scrutiny of historical records indicates that the actual limit was somewhat farther upstream. A letter to the Virginia Fish Commission (Anon. 1875) states that shad were caught at Kellysford (sic), 28 mi above Falmouth Falls. Downman (1883) stated that shad were taken in large quantities at Beverly's Ford (just above Remington), 33 mi above Falmouth Falls. The Virginia Fish Commission (1875) stated that shad and herring ascended the Rappahannock above the Orange and Alexandria Railroad (Remington). McDonald (1889) reported that shad ascended almost to the base of the Blue Ridge, which is consistent with a range of at least Remington. Thus a conservative estimate for the historic limit of the shad run is Remington (Beverly's Ford), approximately 33 mi above Falmouth Falls (the purported limit) and 188 mi upstream of the river mouth.

River herring, being smaller than shad, are able to ascend farther upstream. Therefore, in most cases their spawning runs equal or exceed those of the shad. Downman (1883) reported that herring were caught in large quantities as far upstream as Fauquier Springs, 15 mi above Remington, and 202 mi above the river mouth.

The historical record of the range of the striped bass in the Rappahannock River is inconclusive. References to the extent of their migration are lacking. The only point that can be made with certainty is that their range was at least as great as it is now.

The present extent of the range of all these species is the Embrey Dam (built c. 1830) located just above Fredericksburg (Jack Randolph, VCGIF, pers. comm.; Joseph Loesch, VIMS, pers. comm.).

## York River System

The York River (including the Mattaponi and the Pamunkey) is perhaps unique in that there are no dams across it to block the passage of anadromous fishes. Thus the amount of river available to the fishes is essentially the same as it was in Colonial times. The upstream limits of fish migration are set by natural falls, shoals, and a general shallowing of the river (Jack Randolph, VCGIF, pers. comm.;

Joeseph Loesch, VIMS, pers. comm.). It is interesting to note that in the case of the Mattaponi and the Pamunkey, man's activities (in this case the use of the rivers for navigation) may have actually at one time extended the upstream limits of the migrations. Stevenson (1897) claimed that decreased use of the river for navigation allowed the channels to fill with sand, thus restricting the range of the fishes.

The historical ranges for shad and herring were: above Milford on the Mattaponi River, and the entire length of the Pamunkey River, going into the North and South Anna Rivers which form it (Virginia Fish Commission 1875). There is no historical information on the range of the striped bass in these waters.

The present limit of the range of shad and herring in the Mattaponi is at least the vicinity of the U.S. 301 bridge at Milford (Jack Randolph, VCGIF, pers. comm.) or for shad, at the very least the U.S. 360 bridge (William Kriete, VIMS, pers. comm.). Shad and herring now ascend the Pamunkey River to its source, at the juncture of the North and South Anna Rivers (Jack Randolph, VCGIF, pers. comm.; John White, VEPCo, pers. comm.). Striped bass are currently caught as far upstream as the U.S. 360 bridges on the Mattaponi and the Pamunkey and may ascend further (William Kriete, VIMS, pers. comm.).

James River

Shad and herring originally ascended the entire length of the James River and continued up the Jackson and Cowpasture Rivers and their tributaries as far as Covington (Virginia Fish Commission 1875; McDonald 1889). This amounts to 370 mi upstream of the river mouth. Striped bass were caught as far upstream as Balcony Falls (near Glasgow) and were caught in large numbers at Swift Island (Midway Mills, below Lynchburg), 102 mi above Richmond (McDonald 1889). The present limit for all species is Bosher Dam (built 1837) above Richmond (Atran et.al. 1983). Several dams in the Richmond area restrict the numbers of fish going upstream, particularly in low flow years, but Bosher Dam effectively forms an insuperable barrier.

The biological significance of striped bass migrations up rivers above the fall line is uncertain. Although there is no doubt that these migrations did occur, recent evidence based on historical reports (White et al. 1984) indicates that these were not spring spawning migrations, but rather fall feeding migrations composed of small male fish. Apparently, striped bass never spawned upstream of the fall line. What effect (if any) the curtailment by dams of these feeding migrations has had on striped bass populations is unknown.

## Impediments

### Water Quality

A reach of stream might function as a barrier to upstream migrating fish if its water quality was sufficiently degraded that the species of interest could not or would not pass through it. In the context of this report, investigation of such potential barriers was limited to the James and Rappahannock Rivers, because anadromous species do now successfully use the York system, indicating that water quality there is not a limiting factor.

The SWCB, in response to our request, was itself unable to make a direct assessment of the water quality vs. fish passage problem on the James River. However, the Rappahannock has no significant pollutant inputs between Fredericksburg, the present upstream limit of movement, and Remington, the historic limit.

The SWCB did provide data on major dischargers on the James system from Richmond, (the present limit) to Covington (the former boundary) as well as monthly water quality monitoring data for the 1982-84 period at stations throughout this 230-mile reach. On the basis of this information, there is no cause to believe that poor water quality will prevent upstream migrations at any point. Between Richmond and Lynchburg, the principal recognized

discharger is the Bremo Power Station, a 235 MW steam-electric plant operated by Virginia Power. The thermal discharge from the Bremo Power Station is elevated 15 C and extends 1 km downstream. However, this plume is a maximum of 50 m wide in the 200-m wide river, and fish should have no trouble avoiding it (Woolcott 1985).

From Lynchburg upstream, temperature, dissolved oxygen and pH are within the range of tolerance for the species of interest. Other parameters (e.g. heavy metals, fecal coliforms) indicate that the river is less than pristine, but not sufficiently degraded to prohibit passage. However, the monitoring program was not adequate to fully assess all potential chemical deterrents (e.g. phenols and other odors, color changes). For example, the SWCB monitoring data indicate that the Jackson River at Covington is not degraded, although the water is turned orange-brown by paper mill pollution for a distance of 20 km (Bishop 1985).

It appears, however, that the James River itself, from the confluence of the Cowpasture and the Jackson Rivers downstream to Richmond, will not prohibit spawning runs of anadromous fish due to poor water quality. While both point-source and nonpoint source pollution does enter the James, it is likely not of such magnitude to be a deterrent to fish movement, particularly in the spring high-water period when anadromous fish are migrating.

## Dams

### Rappahannock River.

One dam, Embry Dam, is present on the Rappahannock River at Fredericksburg (Table 1), and is the current upstream limit of the migrations of anadromous fishes. There is nothing upstream of this dam to prevent fishes from the realization of their historic range, at least on the mainstem of the river.

### York River System.

There are no dams on the York, Mattaponi, or the Pamunkey Rivers.

### James River.

There are twelve dams on the James River that impede or would impede (were fish not already impeded by dams further downstream) the spawning runs of anadromous fish. Five of these dams are in the Richmond area (Figure 2 and Tables 2 - 6) and the other seven are around or slightly upstream of Lynchburg (Figure 3 and Tables 7 - 13). Their removal, or the establishment of fishways at the Richmond area dams would restore 139 miles of mainstem James River to the ranges of these fishes. Similarly, the removal of the Lynchburg area impediments would restore an additional 88 miles of mainstem river to their spawning range. The total length of river restored as a result of the removal of all impediments would be 226 miles, a 200% increase.

TABLE 1

Embry Dam

Location: Fredericksburg, approx. river mile 150

Date built: 1925 and 1938

Height: 22'

Reservoir Area: 60 acres

Use: Water supply, being refitted for hydroelectric

FERC project no. 7490

Owner: City of Fredericksburg

Note: VCGIF is trying to get fishway constructed here as a condition of licensing.

Figure 2. Dams on the James River in the City of Richmond.

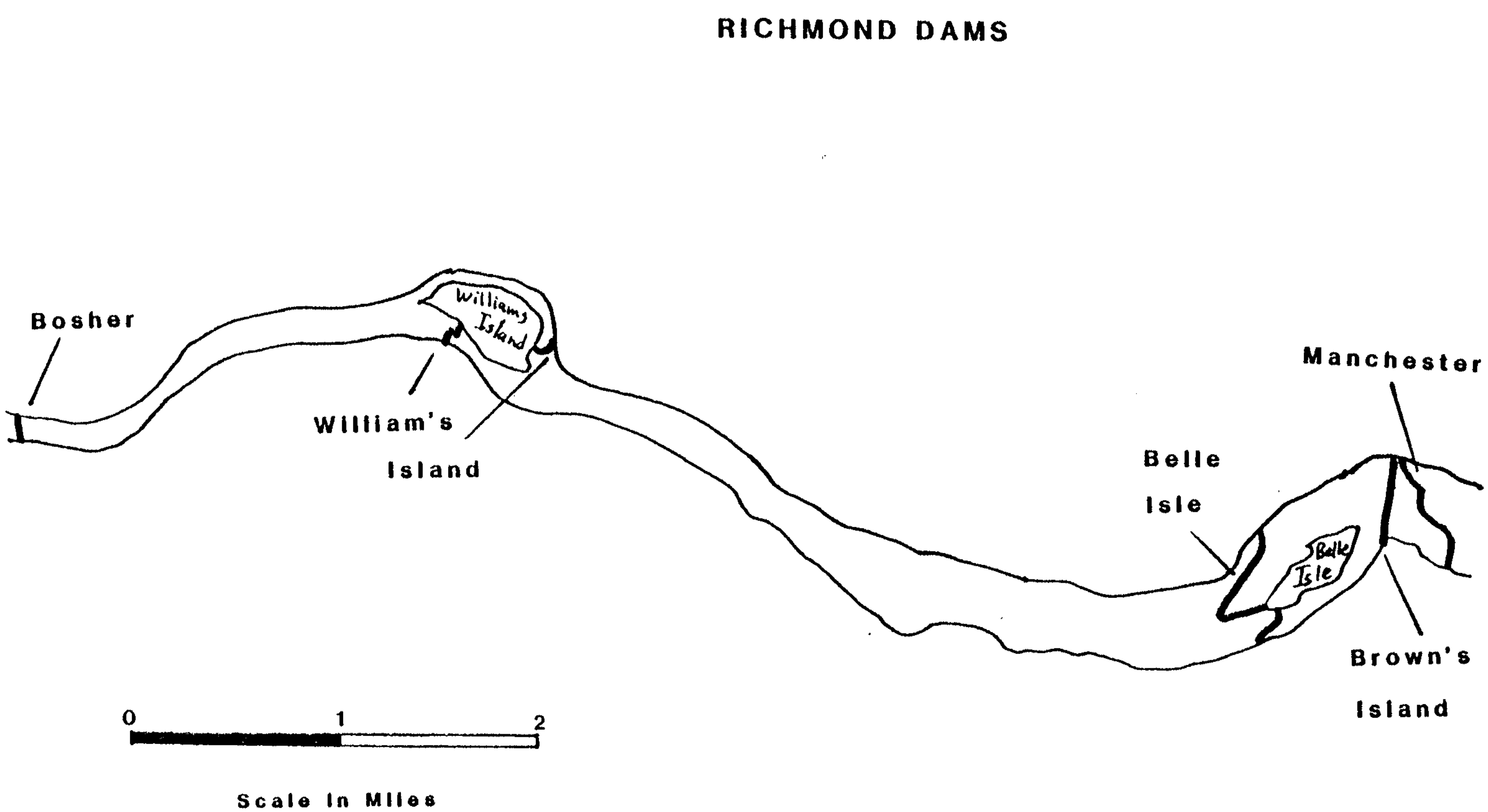


TABLE 2

Manchester Dam

| | |
|---|---|
| Location: | Richmond, Henrico County, river mile 105.1 |
| Date built: | 1920 (1804) (1886) |
| Height: | 1-6' |
| Reservoir Area: | 15 acres |
| Use: | Recreation (originally hydroelectric, water supply) |
| FERC project no. | 6480 |
| Owner: | City of Richmond |
| Notes: | Presently passable by fishes only at very high river flows (Rizzo 1983). May be redeveloped for power. |

TABLE 3

Browns Island Dam

Location: Richmond, Henrico County, river mile 105.2

Date built: 1901

Height: 9'

Reservoir Area: negligible

Use: none (originally water diversion for hydroelectric)

FERC license 3504 pending

Owner: City of Richmond

Notes: Abandoned, but may be rehabilitated. Currently negotiable by fishes at most river flows through damaged portions.

TABLE 4

Hollywood/Belle Isle Dam

| | |
|---|---|
| Location: | Richmond, Henrico County, river mile 106.1 |
| Date built: | 1830 and 1909 |
| Height: | 4-16' |
| Reservoir Area: | 20 acres |
| Use: | none (originally water supply) |
| FERC project no. | 3024, expiration 2002 |
| Owner: | City of Richmond |
| Notes: | In two sections, one on either side of Belle Isle. Northern segment with two breaches 40-60' in length. Negotiable by fishes at practically all river flows through the breaches (Rizzo 1983). |

TABLE 5

William's Island Dam

| | |
|---|---|
| Location: | Richmond, Henrico County, river mile 110.7 |
| Date built: | 1920's |
| Height: | 7' |
| Reservoir Area: | 80 acres |
| Use: | Water supply (originally navigation) |
| Owner: | City of Richmond |
| Notes: | Intact. In two segments, one on either side of William's Island. South side impassable except at high river flows (Rizzo 1983). |

TABLE 6

Bosher Dam

Location: 2 mi NW of Bon Air, Henrico County, river mile 113.3

Date built: 1830's

Height: 10'

Reservoir Area: 425 acres

Use: Hydroelectric (originally navigation)

FERC project no. 3029, expiration 2002

Owner: C+O Railroad owns dam, City of Richmond owns water rights and head gates.

Note: Currently an insuperable barrier to fish migrations.

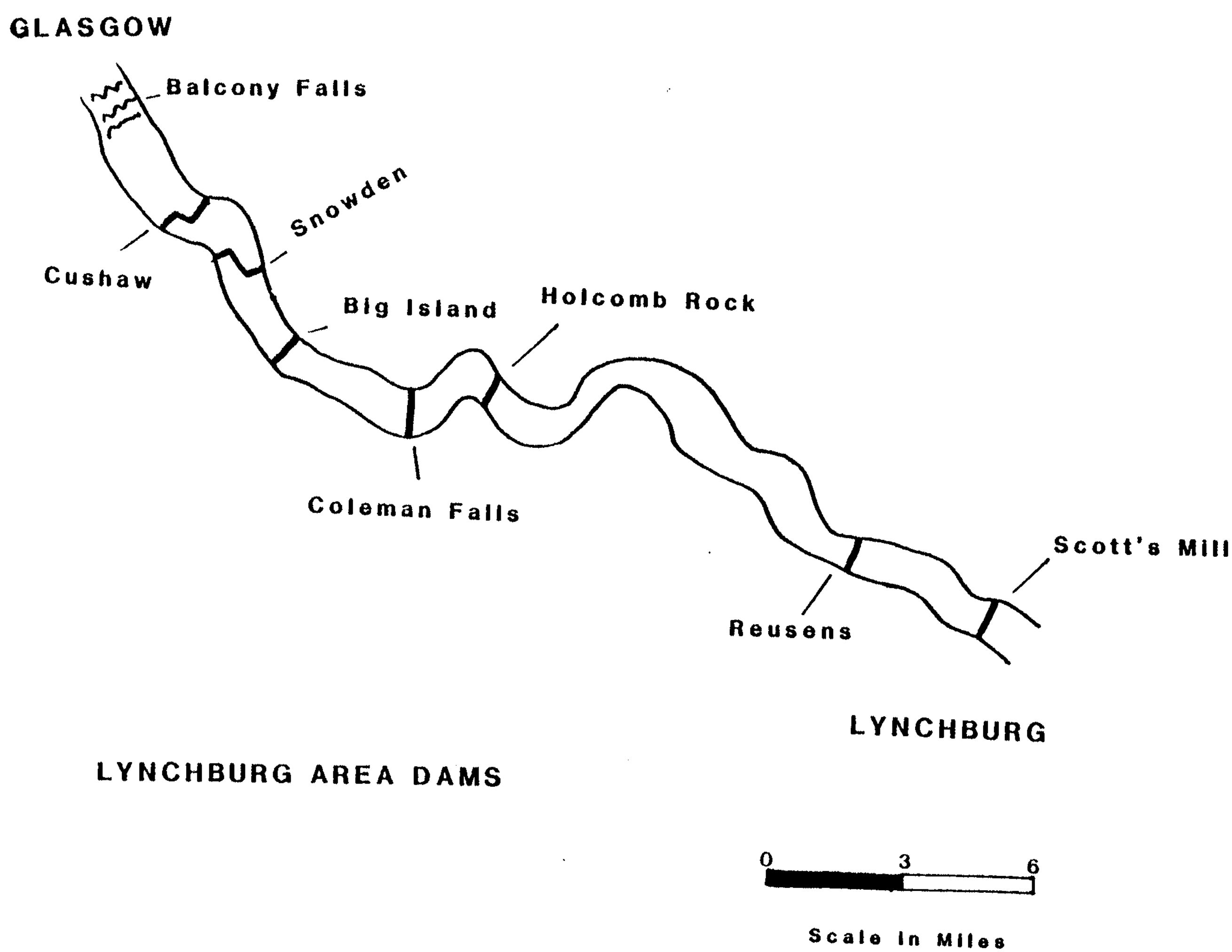



Figure 3. Dams on the James River from Lynchburg to Glasgow.

TABLE 7

Scots Mill Dam

| | |
|---|---|
| Location: | City of Lynchburg, Amherst County, river mile 252.1 |
| Date built: | 1840's |
| Height: | 20' |
| Reservoir Area: | 370 acres |
| Use: | Water supply (originally navigation) |
| Owner: | APCo |

TABLE 8

Reusens Dam

| | |
|---|---|
| Location: | 3 mi NW of Lynchburg, Amherst County, river mile 255.6 |
| Date built: | 1840's, (1903 hydro) |
| Height: | 45' |
| Reservoir Area: | 500 acres |
| Use: | Hydroelectric (originally navigation) |
| FERC project no. | 2376, expiration 1993 |
| Owner: | APCo |

TABLE 9

Holcomb Rock Dam

Location: 0.5 mi N of Holcomb Rock, Amherst County, river mile 264.0

Date built: 1840's

Height: 14'

Reservoir Area: 105 acres

Use: Hydroelectric (originally navigation)

FERC project no. 2901, expiration 2001

Owner: Owens-Illinois Corp.

TABLE 10

Coleman Falls Dam

Location: Coleman Falls, Amherst County, river mile 266.2

Date built: 1851 (1900, 1984)

Height: 20'

Reservoir Area: 135 acres

Use: Hydroelectric (originally navigation)

FERC project no. 5456

Owner: Owens-Illinois Corp.

TABLE 11

Big Island Dam

| |
|---|
| Location: Big Island, Amherst County, river mile 270.5 |
| Date built: 1840's |
| Height: 11' |
| Reservoir Area: 70 acres |
| Use: Hydroelectric and water supply (originally navigation) |
| FERC project no. 2902, expiration 2000 |
| Owner: Owens-Illinois Corp. |

TABLE 12

Snowden Dam

| | |
|---|---|
| Location: | 2 mi SE of Snowden, Amherst County, river mile 273.7 |
| Date built: | 1920 |
| Height: | 14' |
| Reservoir Area: | 90 acres |
| Use: | Hydroelectric |
| FERC project no. | 5596 |
| Owner: | City of Bedford |
| Note: | This dam is called Bedford Power Dam in Corbett (1977) |

TABLE 13

Cushaw Dam

| |
|---|
| Location: 1 mi SE of Snowden, Amherst County, river mile 274.9 |
| Date built: 1929 |
| Height: 26' |
| Reservoir Area: 115 acres |
| Use: Hydroelectric |
| FERC project no. 906, expiration 2008 |
| Owner: VEPCo |
| Note: This dam is called Snowden Dam in Corbett (1977). |

## Feasibility of Elimination of Barriers

There are 12 dams on the James River and one on the Rappahannock. They are owned by industry, utilities, and municipalities. Because mitigation to facilitate fish passage over or around these structures will involve expenses (sometimes considerable), owners are unlikely to undertake remedial actions themselves without legal direction to do so.

In Virginia, two sources of regulatory/legal actions could be applied to coerce dam operators to make fish passage modifications. The Code of Virginia (i.e. state law) is by far the weaker. Section 29-151 of the Code does require dam owners to provide and maintain fish ladders, but it is rife with exemptions. The penalty for failure to comply is $1.00/day. However, the circuit court is empowered to have fishways constructed at owner's expense. To our knowledge, the law has never been applied.

Real enforcing regulation rests with FERC and is, of course, restricted to hydropower dams, which FERC licenses.

FERC hydropower licenses include "a standard license article that is incorporated into virtually all licenses" (Quentin Edson, Director, FERC Office of Hydropower Licensing, pers. comm.). The article reads as follows:

> "The Licensee shall, for the conservation and development of fish and wildlife resources, construct, maintain, and operate, or arrange for

> the construction, maintenance, and operation of such reasonable modifications of the project structures and operation, as may be ordered by the Commission upon its own motion or upon the recommendation of the Secretary of the Interior or the fish and wildlife agency or agencies of any State in which the project or a part thereof is located, after notice and opportunity for hearing."

In reality, this clause means that the USFWS or the VCGIF can petition FERC to initiate a hearing process at which the petitioner must demonstrate to an administrative law judge that passage facilities would be in the best public interest. The critical elements here are interpretation of "reasonable" facilities/modifications and "best public interests." Facilities can range from a simple breach in an existing structure to fish locks and lifts in the million-dollar range for construction and needing an annual operation budget as well. The ultimate decision on passage facilities through the FERC license route is judicial and based on a cost-benefit appraisal; it cannot be reliably predicted. If the decision does mandate passage facilities, FERC would usually expect them to be constructed in 1-2 years, barring complications. When there is a series of dams on a portion of river, FERC could consider them as a set, if the petitioner so desired. However, in practice, dams are usually considered sequentially, in part because it is difficult to develop effective passage facilities until the fish have actually arrived at the dam.

There is an alternative to compelling dam owners to fund passage facilities. State or federal agencies may themselves undertake partial or complete financial support of these projects, though federal involvement is limited to dams not under the FERC mandate. In Massachusetts, for example, the state Marine Fisheries Commission has constructed numerous fish ladders to facilitate spawning runs of alewife and blueback herring. However, government support for passage projects is a political decision, made on a case-by-case basis, and without clear criteria. Like the outcome of FERC hearings, it cannot be predicted at particular sites.

Our communications indicate that both the FERC regulatory process and government support will be involved in the restoration of anadromous fish runs in Virginia. The scenarios that can be projected with present information follow.

Rappahannock River

All anadromous species now ascend to the base of the Embrey dam at Fredericksburg. This dam is a 60-year old structure owned by the City of Fredericksburg, which has leased it to Hydropower Research, Inc. (HRI) of Portsmouth, Virginia on the condition that it be retrofitted, licensed,

and operated for power production (Wayne Bishop, City of Fredericksburg, pers. comm.). HRI has a license application pending with FERC. The VCGIF will press for the license to require construction of a fishway (Jack Randolph, VCGIF, pers. comm.). The critical aspect will likely be the cost of this facility; if too expensive, HRI will probably abandon the project. In this case, the dam will remain as the upstream limit of anadromous species on the Rappahannock system. However, it is our estimate that a fishway will probably be constructed by 1990, opening the river to shad, alewife, river herring, and possibly striped bass to at least Remington, an additional 33 river miles.

James River Dams: Richmond

Five dams owned by the city of Richmond and operated for power, water supply, and recreation now effectively prohibit further upstream passage of anadromous fish (Figure 2). The Virginia Legislature resolved in 1981 that the feasibility of passage of these dams be investigated by state and local agencies. The resulting report (Atran et al. 1983) concluded that it would be feasible to develop passage facilities, with varying degrees of effort and cost at each dam. Total preliminary cost estimates were $2.5-7.5 million dollars.

The Legislature has directed that passage facilities be developed, with the VCGIF as the lead agency. The City of Richmond has offered some resistance to the VCGIF plans, citing uncertain impacts on river recreation and unreasonable cost assessments. In response to our request, John Randolph, Assistant Executive Director of the VCGIF provided his best current estimate (March 22, 1985) of when and how passage around each dam would be accomplished. The scenario is summarized in Table 14 and proceeds as follows.

The VCGIF has a tentative agreement with the City to breach the lower two dams, Manchester and Brown's Island, pending resolution of esthetics/recreation concerns. These dams should be breached in time for the 1986 spawning run to reach Belles Island dam. This dam may be negotiable by current breaches or modifications will have to be made; it appears that 1987 is a reasonable target date for passage at Belles Island. The next dam, Williams Island, will probably require a gated breach, as it is a water supply dam; another year may be required to achieve passage here. Several years delay is likely in passing fish beyond the final Richmond barrier, Bosher's Dam. The city operates Bosher's Dam as a hydroelectric facility, and it is under the FERC mandate. However, an expensive fish lock may be required here, and state financial support may be necessary to construct it.

TABLE 14

Projected schedule for implementation of fish passage facilities at Richmond dams on the James River.

| | Dam | Action | Target Date |
|---|---|---|---|
| 1. | Manchester | Breach | 1985-86 |
| 2. | Brown's Island | Breach | 1985-86 |
| 3. | Belles Island | Breach (existing) | 1986-87 |
| 4. | Williams Island | Breach | 1987-88 |
| 5. | Bosher's Dam | Fish Lock | 1990-91 |

The earliest practical date for passage around Bosher's Dam appears to be 1991.

Given the political resistance in Richmond and the uncertainties of how the fish themselves will behave as they encounter each dam, it is our opinion that it should not be surprising if the actual time to overcome the Richmond dams is considerably longer.

## James River Dams: Lynchburg Area

Passage at Richmond will open a 139-mile reach of the James River and its tributaries to anadromous fish. Access to the remaining 120 miles is blocked by seven dams within a 23-mile reach beginning in Lynchburg (Figure 3). Passage past these dams is considerably more difficult to predict than for the Richmond dams, as they are owned by two utilities, one industry, and a municipality (Table 15). Although APCo, VEPCo, Owens-Illinois and the City of Bedford have assured us of their intent to accommodate fish passage problems, if and when confronted with them, the nature and timing of their response is not predictable, owing to uncertainties of the requirements to achieve passage.

Six of the dams are presently operated for hydropower and are subject to the FERC mandate. The first in the series, Scots Mill Dam, is owned by APCo, but a private company,

TABLE 15

Projected schedule for implementation of fish passage facilities at Lynchburg area dams on the James River.

| | Dam | Owner | Target Date |
|---|---|---|---|
| 1. | Scots Mill | APCo/LHA | 1995 |
| 2. | Reusens | APCo | 1998 |
| 3. | Holcomb Rock | Owens-Illinois | 2001 |
| 4. | Coleman Falls | Owens-Illinois | 2004 |
| 5. | Big Island | Owens-Illinois | 2007 |
| 6. | Snowden | Bedford | 2010 |
| 7. | Cushaw | VEPCo | 2013 |

Lynchburg Hydro Associates, has recently applied for a FERC license; presumably it, too, will be subject to the FERC mandate.

We assume that each dam will be considered separately and sequentially in the FERC hearing process for two reasons. First, the dams are not under joint ownership. Second, the presence of anadromous fish at the base of the dam will strengthen the petitioner(s) case as well as facilitate design of effective passage facilities.

In the event of this dam-by-dam approach, a minimum 2-3 year period to develop passage facilities is reasonable, given the time required for hearings, judicial decisions, design, and construction. This scenario (Table 2) would open the remainder of the James system to anadromous fish (except, perhaps, striped bass which might be barred by Balcony Falls) by 2013.

This estimate should be regarded as optimistic. Because each of these dams is operated for hydropower, effective passage facilities will probably be relatively expensive if they are not to interfere with power production. The FERC decision-making process centers on cost-benefit determination. Neither costs nor potential benefits can be estimated at this time. It is conceivable that either decision will not require development of passage facilites

or that the operator will decide to abandon the dam rather than implement them. In either instance, the dam will remain as a barrier until other, as yet unknown, resources are marshalled to address the problem.

## Literature Synthesis

This section consists of a discussion of the biological capabilities of the American shad, alewife, blueback herring, and striped bass with regard to fish passage, and technical considerations for passage of these fish in fishways and highway culverts. The reproductive biology of these species has been reported and summarized elsewhere and is not included here. The interested reader is directed to Loesch and Lund (1977), Bain and Bain (1982), Atran et al (1984), and Richkus and DiNardo (1984).

### Biological Considerations

Anadromous fishes live the majority of their lives in the estuarine or marine environment but return to freshwater to spawn. A necessary feature of their life history is the spawning migration which is the mechanism that connects these two different environments and allows the fishes' life cycles to be completed.

The nature of these migrations varies greatly among the different anadromous species. Migrations range from the small and uneventful movements of some striped bass populations, which may lazily travel only thirty miles upstream from the mouth of a large river, to the long arduous trek of the Pacific salmon, which must often fight strong currents over a thousand miles and leap ten foot waterfalls in an effort to reach their natal stream. These migrations are also influenced by the nature of the river system in which they occur. Spawning migrations of the same species in two adjacent rivers may be quite dissimilar. The availability of suitable spawning conditions or the presence of impassable falls are examples of factors that can greatly influence the length of the spawning migration.

The task for the fish is to get from its estuarine or marine environment at sea level to its freshwater spawning ground, often several thousand feet above sea level, within a specified time, and within certain bioenergetic constraints. Through prehistory, anadromous fishes have evolved the capabilities to do so. These capabilities include adaptations that allow the fish to overcome the naturally occurring melange of physical, chemical, and biological challenges faced along the way.

The forces that oppose the upstream movement of the fishes originate as a result of the vertical distance between sea level and the spawning grounds. The main force is the velocity of the water moving downstream which impedes the upstream movement of the fish. This water velocity is influenced by characteristics of the streambed and watershed, including water depth and gradient. In addition to its effect on water velocity, gradient can have a direct effect on fish migrations when it comes in the form of waterfalls and other forms of passable and impassable barriers. Other factors that can impede upstream movement of fishes, but are not normally encountered as obstacles, include temperature, photoperiod, and light intensity.

As fish move upstream, they require a water of sufficient quality to sustain their endeavors. The quality of water needed is perhaps elevated over what they would normally require because of the high metabolic cost of the migration. An added energy expenditure for these fish, in addition to that required for swimming, is needed for the maturation of sex products, which occurs concurrently with the migration (Glebe and Leggett 1981b; McKeown 1984).

Assuming adequate water quality, the biological considerations most important to upstream fish passage are jumping ability, swimming speed, and swimming endurance

(Evans and Johnston 1980). The inability of East Coast anadromous fishes to utilize some fish passage facilities easily negotiated by Pacific salmon suggests that these fish may be deficient in one or more of these areas. Another important factor, but difficult to assess, is motivation. Swimming performance is a function of both capability and motivation (MacPhee and Watts 1976).

Common sense dictates that, in addition to swimming and jumping ability, anoxic conditions and other life-threatening water quality conditions such as excessively high or low pH and temperature extremes, can block migrations. Less dramatic changes in water temperature can also affect the timing of migrations (Saila et al. 1972).

Swimming speed is often divided into three categories. The first of these is burst velocity, which represents the maximum possible speed of the fish. This speed requires such effort by the fish that it can only be maintained for very brief periods of time, generally defined as 5 to 10 seconds. Prolonged speed is the speed that the fish can maintain for longer periods (20 sec to 200 min), but which is still stressful and results in fatigue. Sustained speed (cruising speed) is the final category. It is the speed that the fish can maintain for extended periods, is not stressful, and does not result in fatigue (Beamish 1978).

In practice, however, the differences between prolonged speed and sustained speed are often blurred. This is because of the often subjective determinations of fatigue, the difficulty in ascertaining stress in the field, and inconsistency in the use and definitions of these terms by researchers (e.g. Jones 1968; MacPhee and Watts 1976; Ministry of Environment 1980). The most important aspects of swimming performance with respect to fish passage are burst velocity and, in longer fishways, prolonged swimming speed.

American shad.

American shad compare favorably with many species of Pacific salmon in their swimming capacities, both burst speed and sustained speed. Burst speed has been measured at 3.5 to 4.0 m/s (Weaver 1965). Burst velocity is not a limiting factor in the use of fish passage facilities by American shad (Boyd Kynard pers. comm.). Sustained velocities are in the range of 0.65 to 0.75 m/s (Beamish 1978), and again should not limit their use of passage facilities.

The inability of American shad to successfully utilize many fishways can be traced to two factors. The first is that they do not jump over obstacles (Boyd Kynard pers. comm.). The second is that they seem to be confused by turbulence (Katz 1976), perhaps losing their directional

cues. The result of these two factors is that American shad require a laminar flow of water the entire length of the fishway, an engineering problem that will be discussed in a subsequent section.

Glebe and Leggett (1981a) showed that the normal migratory activities of American shad resulted in extreme (45-60%) somatic weight loss and associated energy depletion, and that up to 50% of body protein and 70% of body lipid (fat) was used to fuel migrations. It is clear that there is some upper limit to the energy expenditures these fish can incur on their migrations, for example in using fishways, and still successfully spawn.

Alewife.

In general, alewives are more successful in using fish passage facilities than are American shad. Burst velocity of adult alewife (27-31 cm) is in the range of from 4.2 to 4.8 m/s (Dow 1962). Although, like shad, alewives will not jump over obstacles, they are apparently less confused by turbulence (Steve Rideout pers. comm.; Buzzy DiCarlo pers. comm.).

The metabolic costs to alewives of passage through a pool and weir fishway was studied by Dominy (1971). The slight increases noticed in blood lactic acid concentrations indicated that, in this study using rested fish, fishway passage was not a severe exertion.

Blueback herring.

Little research has been conducted to assess the passage capabilities of the blueback herring. Given the physical similarities between the alewife and blueback herring, it would seem that swimming performance should be similar for both species. However, field observations indicate that they may in fact be quite dissimilar (Steve Rideout pers. comm.). Despite the fact that neither species will jump over obstacles, blueback herring are much less successful in using fish passage facilities than are alewives. This suggests that the observed differences between the two species in negotiating fishways may be due to differences in swimming ability, or in behavior.

The swimming abilities of the blueback herring have not been reported in the literature. Behaviorally, blueback herring have been shown to avoid changes in light intensity caused by shading (Collins 1952). Conceivably, this could result in a reluctance on their part to use fishways. Field observations, however, tend to refute this line of reasoning. For example, the fishway type that they are most successful in using (the denil type) involves more alternating shadows and light than fishways negotiated less successfully. Steve Rideout (pers. comm.) feels that (for all the alosine species) shadows may be an inhibitory factor

early in the run, but as spawning approaches, any timidity they may have vanishes as their urge to reach the spawning grounds increases.

A final reason for the lesser usage of fish passage facilities by blueback herring than by alewives may be that blueback herring have innately less impetus to use the facilities. Blueback herring spawn under riverine conditions, while alewives typically spawn in ponds or more lentic habitats. The river below a dam may be suitable spawning habitat for blueback herring, but unsuitable for alewives. Consequently, the alewife has greater motivation to pass over the dam and may strive harder to do so.

Striped bass.

Little research has been conducted on the swimming and jumping ability of striped bass (particularly adult striped bass) relative to fish passage considerations. Kerr (1953) tested immature striped bass (7-14 cm) and found them to be good swimmers. He extrapolated these results to theorize that adult striped bass were powerful swimmers. However, this appears not to be the case.

Chadwick and Skinner (1967) tested the swimming ability of adult striped bass (≥ 86 cm total length) and found the "maximum cruising speed" (which they defined as the speed that 90% of the fish could endure for 45 min) to be from

0.46 to 0.61 m/s. Endurance was related to size and peaked in the size range of 56-70 cm, and then decreased. They concluded that water velocity in fishways designed for striped bass should not exceed 0.46 to 0.61 m/s.

Even when water velocities are within the range presumed negotiable, striped bass seem to be reluctant to use passage facilities. Chadwick and Skinner (1967) investigated numerous design configurations in an experimental vertical slot fishway and found that even under the best conditions, only 23.5% of the striped bass used the facility. A similar percentage was found by Fisk (1959).

Boyd Kynard (pers. comm.) stated that immature striped bass use fish ladders on the Connecticut River; however, their numbers were few in relation to the numbers remaining below the dam. Because these fish are on an alimentary (feeding) migration rather than a spawning migration, and an abundance of prey is congregated below the dam, there may be no impetus for the striped bass to utilize the facility.

Evidence that high concentrations of total dissolved solids can block the spawning migrations of striped bass is presented by Radtke and Turner (1967). They found that fish did not enter a section of the San Joaquin River that had TDS > 350 ppm. However, many tidal spawning streams routinely experience TDS concentrations much higher than

this (up to 2000 ppm) with no apparent inhibitory effect on striped bass (Bain and Bain 1982).

## Technical Considerations

Simply put, the design of fish passage facilities entails bringing the requirements for passage in line with the fishes' capabilities. Fishways dissipate the energy of the water as it changes elevation, thus reducing velocity. Different types of fishways accomplish this energy dissipation by different means. An undesirable by-product of this energy reduction is often a turbulent, as opposed to laminar, water flow. Again, different fishway types differ in the amount of turbulence they cause.

In facilities intended to pass more than one species of fish, it is necessary to design the facility with the requirements of the "weakest" species in mind. General requirements for upstream fish passage, summarized by Evans and Johnston (1980), include: a resting area below the obstacle; individual jumps of minimum size; water depths and velocities within the required ranges; resting pools en route; and a resting pool at the upstream end. The application of these requirements to Virginia's fishes is complicated by the fact that the passage abilities of our species with regard to water velocities, depths, and other factors are largely unknown.

The analysis of technical aspects of fishway design and effectiveness for different species, in the presence of few detailed studies designed to assess this, can be aided by reviewing what has been built and what has worked. The presence of fish upstream of fish passage facilities, in the absence of other explanations, must be considered as prima facie evidence of the success of the facility in passing fish. The efficiency of the facility may be assessed by comparing the numbers passed above the facility with those aggregated below.

Fishways.

Experience has shown that the earliest fishway designs and some newer ones capable of passing more robust species often do not work for shad, herring, or striped bass (Henry 1976; Miller et al. 1982; Atran et al. 1983; Rizzo 1983). Although it is possible to capture these species below dams and physically transport (truck) them around dams (Layzer 1979), and often desirable to speed up restoration efforts where a fishway is planned, transportation is not a feasible long-term solution to fish passage problems (Rizzo 1983).

Shad, alewives, blueback herring, and striped bass have successfully passed through navigation locks, when they were operated for the purpose of passing fish (Nichols and Louder 1970). Wooley and Crateau (1983) have documented striped

bass passage through navigation locks during normal lock operation, although the numbers passed were small in relation to the numbers present below the locks.

More advanced fishway types such as pressure locks and mechanical fish lifts have been more successful at passing these species (Henry 1976). The use of a fishlift at Holyoke Dam, Massachusetts has resulted in the restoration of runs of 380,000 American shad, 420,000 blueback herring and 510 striped bass into the Holyoke Pool of the Connecticut River (Moffitt et al. 1982). However, these lifts are very expensive, and therefore practical only at major hydroelectric facilities.

Three main types of fishways are in general use for the passage of anadromous alosids. These are: 1) the pool and weir fishway; 2) the vertical slot fishway; and 3) the denil fishway. All achieve the desired result, bringing the water velocity and vertical distances involved within the capabilities of the fish, although in different manners. Figure 4 shows the general characteristics of these different fishway types. These fishway types vary somewhat in there effectiveness in passing anadromous alosids and striped bass, and their ability to perform over a range of water flows.

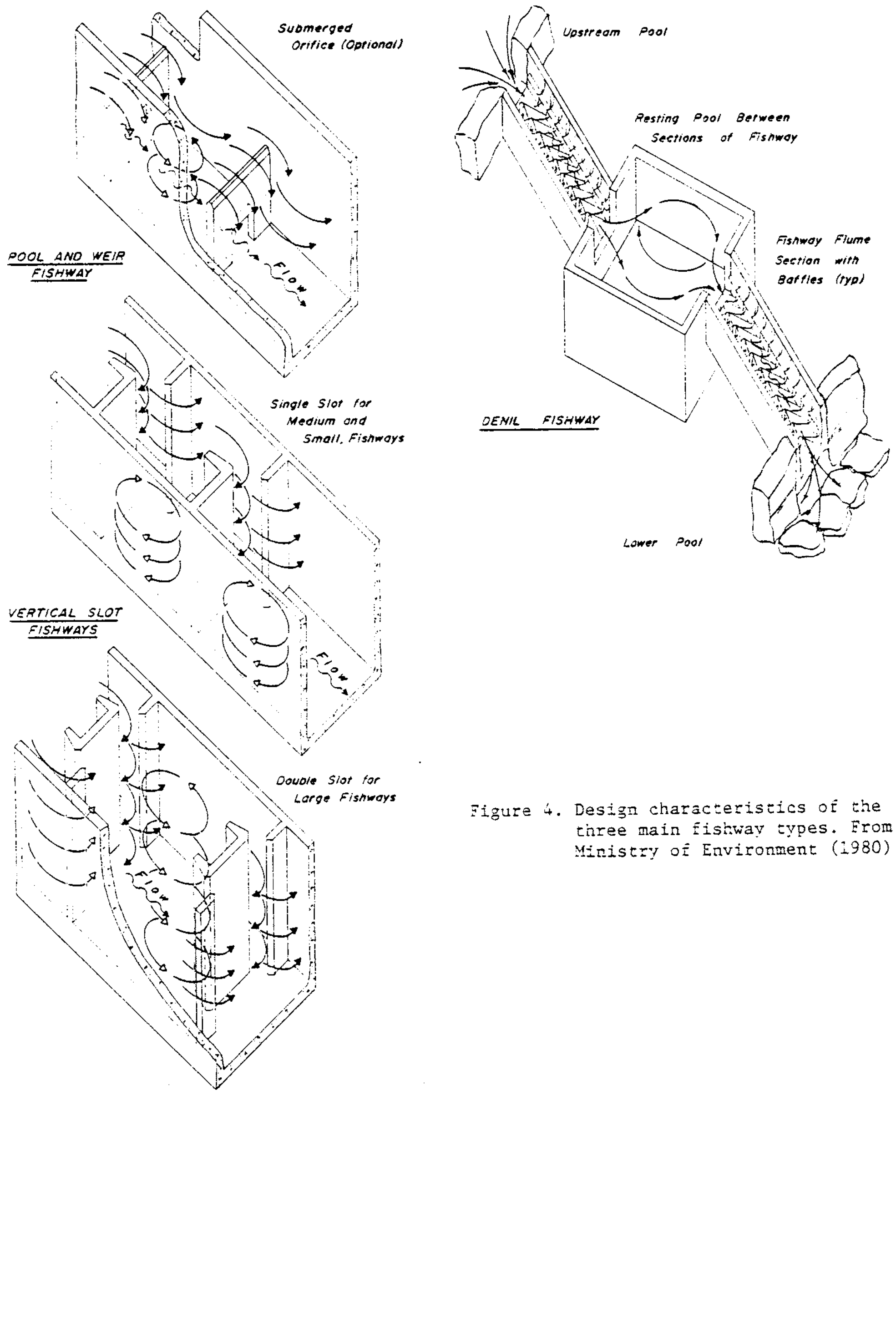



Figure 4. Design characteristics of the three main fishway types. From Ministry of Environment (1980).

The pool and weir fishway (Figure 5) is one of the oldest and most widely used fishway types (Decker 1967). A pool and weir fishway consists of a series of vertical partitions (weirs) installed at intervals along the length of a specially constructed channel (Ministry of Environment 1980). This creates a series of pools, each one slightly lower than the previous one. The weirs are often notched and may also have a submerged orifice to allow fish to ascend from one pool to another without jumping over the weirs. A major problem with the pool and weir fishway is that they need to be adjusted for variations in water flow. Often as little as a few inches difference in water level will change the hydraulic characteristics such that it will not pass fish (Decker 1967).

Properly designed pool and weir fishways will pass alewives and immature striped bass, and in some cases, blueback herring and shad. In many cases though, pool and weir fishways are too turbulent for shad (Boyd Kynard pers. comm.). Design considerations for the alosine species include no more than an 8 inch drop between weirs, and pools as long and deep as possible (DiCarlo pers. comm.). Minimum pool depths are 8 inches for herring and 12 inches for shad. Desirable depths are 2 to 3 times greater.

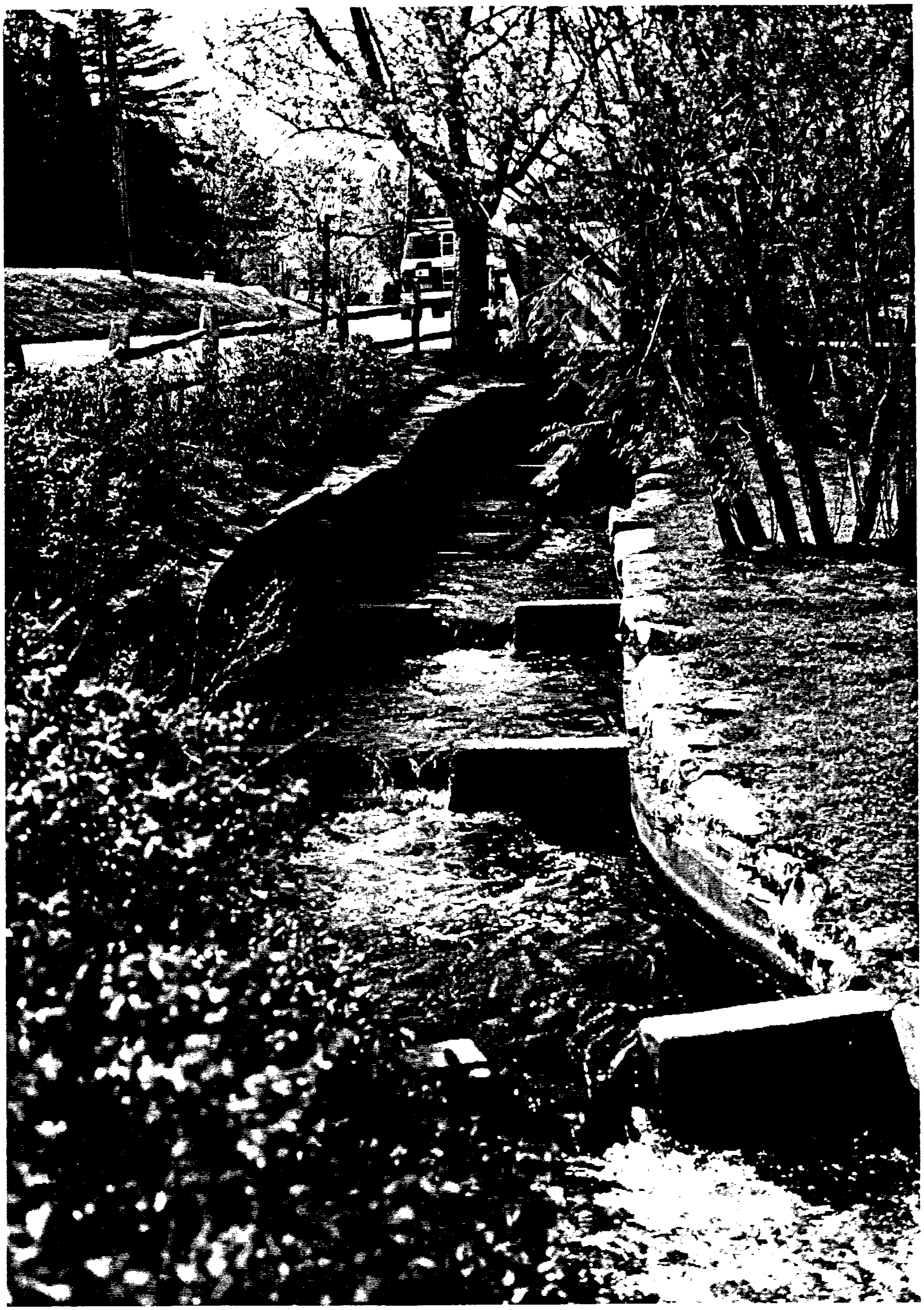


Figure 5. Pool and weir fishway.

The vertical slot fishway also creates a series of pools. However, the pools are separated by partitions with a single vertical slot extending the full height of the partition (Ministry of Environment 1980). As a result, the vertical slot fishway can operate over a wider range of water levels and needs no adjustment (Decker 1967).

Properly designed vertical slot fishways will pass American shad, alewives, immature striped bass, and less readily, blueback herring. An important modification from the standard vertical slot design for the passage of these species is the inclusion of sill blocks, which lessen turbulence (Steve Rideout pers. comm.). Other design considerations for these species ideally include a 9 inch rise per pool to lessen turbulence (Steve Rideout pers. comm.), although a 12 inch difference between pools may be adequate.

The denil fishway (Figure 6) is a section of channel with a series of replaceable baffles that are affixed to the floor and sides at 45 degree angles (Ministry of Environment 1980). It is different from the pool and weir and vertical slot fishways in that it does not entail a series of pools. The baffles operate in such a way that water velocity is differentially slowed in the water column. Water velocity in the chute is fastest at the surface, and slowest at the

bottom, which is where the fish ascend (Everhart et al. 1975). Denil fishways also work effectively over a range (2-3 feet) of water levels (Decker 1967). An advantage of the denil fishway over the other types is that it can be built at a greater slope, thus a shorter fishway is required for the same difference in elevation.

Properly designed denil type fishways will pass American shad, alewives, blueback herring, and immature striped bass (Rideout pers. comm.). Design considerations for the denil fishway include a slope of from 1:5 to 1:7. Thus for each one foot difference in elevation, 5 to 7 feet of fishway chute is required. In longer fishways, there should be a maximum of 35 feet of fishway between resting pools (DiCarlo pers. comm.).

Culverts.

Highway culverts can impede the migrations of anadromous fish when they alter one or more of the following factors: water depth, water velocity, water flow (i.e. laminar vs turbulent), and streambed gradient. Through careful design of new culverts, or retrofitting of old ones, these problems can be avoided or corrected, thus allowing passage of fish (Evans and Johnston 1980).

Different culvert types present differing challenges to upstream migrating anadromous fish. No one type is better

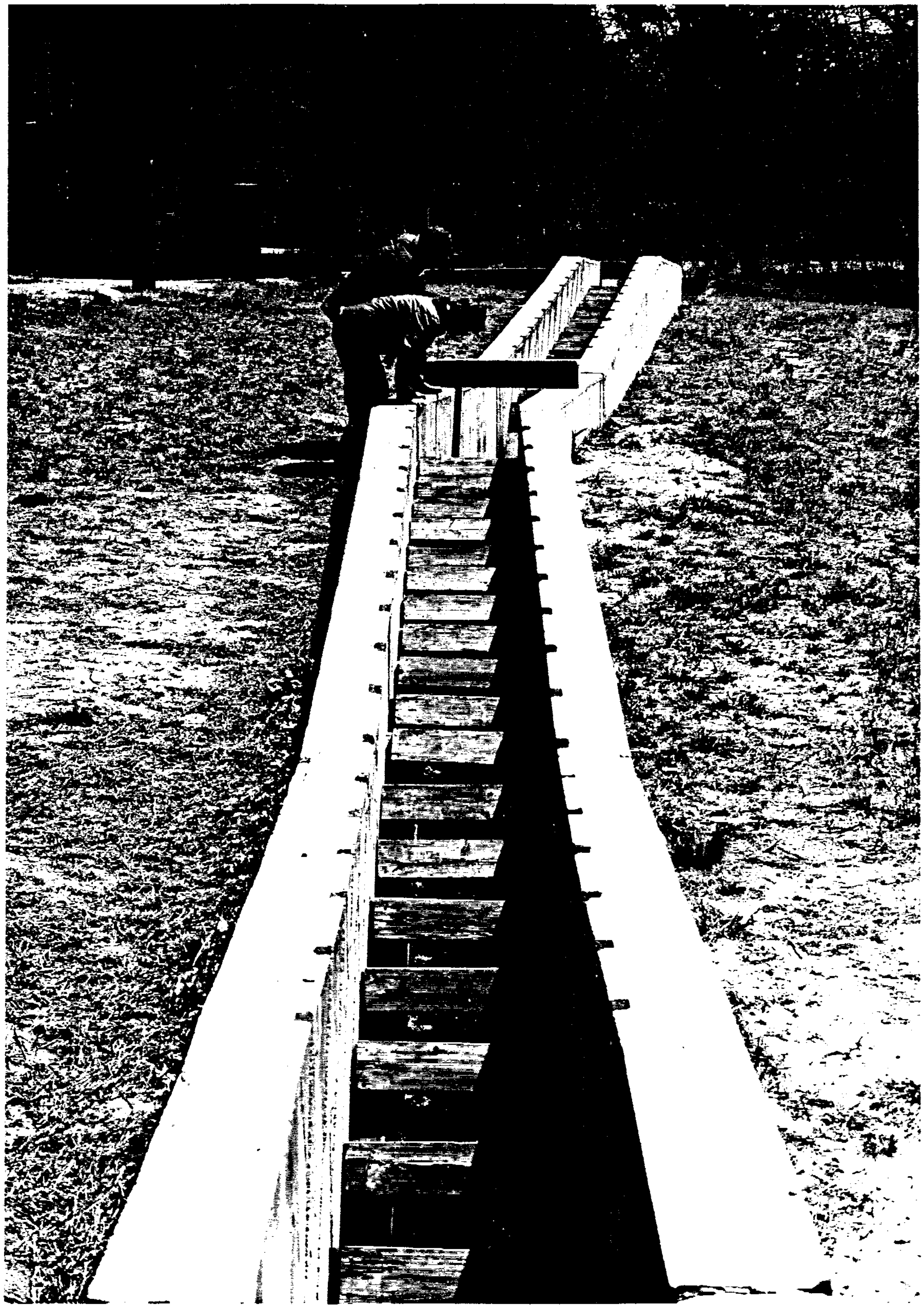


Figure 6. Denil fishway.

than the others in every situation. Nonetheless, some generalizations can be made. Corrugated metal arch culverts that do not disturb the stream bottom present the least problems for migrating fish. Box culverts can usually be suitable for fish passage if the stream bottom is not disturbed, or if the concrete bottom is sunk six inches below the stream bottom (Evans and Johnston 1980). Round corrugated metal pipe culverts are the least desirable from a fish passage standpoint, because they reduce the cross-sectional area of the stream, thus increasing water velocity. This problem is exacerbated when the stream grade is not close to zero. These and further engineering specifics relative to fish passage (although most specifics pertain to salmonids) are presented in Dane (1978) and Evans and Johnston (1980).

The following design factors for culverts should be adhered to in order to ensure fish passage of anadromous alosids (note: most of this information is based on personal communication with B. DiCarlo; other references are added as appropriate). The bottom of the culvert (box or pipe) should be even with or below the stream bottom. In addition to helping maintain water depth, this prevents a vertical drop between the downstream end of the culvert and the stream, which would impede these species since they do not jump.

Existing culverts with vertical drops can be retrofitted with a simple pool and weir structure to eliminate the need for the fish to jump (Figure 7).

The culvert should not be any wider than is necessary, because the excess width reduces water depth. If extra width must be maintained, a trough running down the center of the culvert will help to maintain water depth. At road crossings with multiple culverts, making one culvert lower than the other(s), or the placement of baffles across the openings of all but one culvert, will help direct low flow into one culvert, keeping water depth as great as possible. A water depth of 12" should serve to pass spawning adults of all the alosine species. An 8" depth is sufficient to pass herring only. Too great a water volume in a culvert should also be avoided. Culverts should not be submerged below the water surface because herring, which swim within a foot of the waters surface might not be able to find the attractant flow. As a general rule, culverts should not be more than half full of water.

Culverts should be installed where the streambed gradient is at or very near zero (Ministry of Environment 1980). This is especially true for pipe culverts (Evans and Johnston 1980). Unfortunately, this is not always possible. If the culvert must be inclined, a series of weirs notched in the

Figure 7. A culvert retrofit to eliminate vertical drop.

center should be installed, spaced at 8" differences in elevation. This should allow passage of all species. Care should be taken, however, to ensure that water flow remains laminar.

# SUMMARY

## Range Determinations

There is one dam on the Rappahannock River and twelve on the James River that form actual or potential barriers to the migrations of anadromous fishes. The elimination of these barriers would result in the restoration of 47 miles and 200 miles of mainstem river on the Rappahannock and James Rivers, respectively. While the elimination of all these barriers probably will not be forthcoming in the near future, indications are that the Embry Dam on the Rappahannock and the Richmond area dams may soon become passable by fishes.

## Impediments

Dams have dramatically lessened the amount of river available to anadromous fishes during their spawning migrations into two of Virginia's three major river systems. This is especially true for American shad and river herring. While herring originally migrated 202 miles (and shad 187 miles) on the Rappahannock River, the present limit of their range is 155 mi. The range available on the James has been

decreased from 370 mi to 140 mi. The amount of river available to fishes on the York River system is essentially unchanged. These dams apparently have not interfered with the spawning runs of striped bass since they typically spawn below the fall line.

## Feasibility

The restoration of spawning runs of anadromous fish to reaches of Virginia rivers which have not seen them since Colonial days will occur, but when and to what extent are questions obscured by political and economic uncertainties. It is probable that alewife, blueback herring, American shad, and some striped bass will reach Lynchburg in the next decade. Also during this time interval, these species will probably gain access to an additional 30+ miles of the Rappahannock River above Fredericksburg. It will likely require at least another 20 years to open the remainder of the James River above Lynchburg to these fishes, and it is conceivable that such an effort could be abandoned as impractical.

## Literature Synthesis

Although the biological capabilities of spawning American shad, alewife, blueback herring, and striped bass with regards to passage of fishways are meager in comparison with those of the Pacific salmon, the capabilities of the alosine species are sufficient to allow them to use relatively inexpensive, commonly used fishway types. The same capabilities will allow these species to pass most highway culvert installations, provided certain design considerations are followed.

## REFERENCES


Anderson, L., and M. Bryant. 1980. Fish passage at road crossings: an annotated bibliography. USDA For. Serv. Gen. Tech. Rep. PNW-117, 10 p.

Anon. 1875. Dams on the Rappahannock: extract of a letter from Kellysford, Aug. 2, 1875. Pages 34-35 in Va. Fish Comm. Annu. Rep. 1875.

Anon. 1984a. Strategic Fishery management plan for the American shad (Alosa sapidissima) in the Delaware River Basin. Prepared for the Delaware Basin Fish and Wildl. Mgmt. Coop. 12 p.

Anon. 1984b. Operational management plan for American shad in the Delaware River. Prepared for the Delaware Basin Fish and Wildl. Mgmt. Coop. 12 p.

Antonnikov, A.F. 1964. Hydroelectric construction and the problem of fish passage facilities. Hydroelectric Construction 3:26-29.

Atran, S.M., J.G. Loesch, W.H. Kriete, Jr., and B. Rizzo. 1983. Feasibility study of fish passage facilities in the James River, Richmond, Virginia. VIMS Spec. Rep. No. 269, 109 p.

Bain, M.B., and J.L. Bain. 1982. Habitat suitability index models: coastal stocks of striped bass. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C. FWS/OBS-82/10.1. 29 p.

Baird, S.F. 1882. Report of a committee of the Wyoming historical and geological society on the early shad fisheries of the North Branch of the Susquehanna River. Bull. U.S. Fish Comm. 1:352-379.

Beamish, F.W.H. 1978. Swimming capacity. Pages 101-187 in Hoar, W.S., and D.J. Randall (eds.) Fish Physiology, Vol. 7. Academic Press, N.Y., 576 p.

Bell, M.C. 1973. Fisheries handbook of engineering requirements and biological criteria. Fish Engin. Res. Prog. Corps Engin., North Pac. Div., Portland, Ore.

Beltz, J.R. 1975. Movement and behavior of adult anadromous alewives, Alosa pseudoharengus (Wilson), in the Parker River, Massachusetts. M.S. Thesis, Univ. of Massachusetts, Amherst, Mass., 65 p.

Beverly, R. 1705. The history and present state of Virginia. The Bobbs-Merrill Co., New York, 171 p.

Bishop, J.W. 1985. Human ecology of the James River. Va. J. of Sci. 36(1):14-17.

Blahm, T.H. 1963. Passage of salmon fingerlings through small tunnels. Trans. Am. Fish. Soc. 92:302-303.

Brown, A. 1891. The genesis of the United States, Vol. 2. Houghton, Mifflin and Co., Boston, Mass., 626 p.

Byrd, W. 1737. Natural history of Virginia, Beatly, R.C. and W.J. Mulley (eds./transl.). William Byrd's Natural History of Virginia. 1940. Dietz Press, Richmond, Va., 205 p.

Carlson, F.T. 1968. Suitability of the Susquehanna River for restoration of shad. U.S. Dep. Int., Md. Bd. Nat. Res., N.Y. Conserv. Dep., Pa. Fish Comm. Rep., 60 p.

Carter, R. 1974. Canoeing white water river guide. Appalachian Books, Oakton, Va., 267 p.

Chadwick, H.K. 1967. Recent migrations of the Sacramento-San Joaquin striped bass population. Trans. Am. Fish. Soc. 96:327-342.

Chadwick, H.K. and J.E. Skinner. 1967. Striped bass fishway and swimming endurance tests. Calif. Dep. Fish and Game. Annu. Rep. 6:31-47.

Chittenden, M.E., Jr. 1976. Present and historical spawning grounds and nurseries of American shad, Alosa sapidissima, in the Delaware River. Fish. Bull. 74:343-352.

Clay, C.H. 1961. Design of fishways and other fish facilities. Dep. Fish. Can., Ottawa, 301 p.

Cole, C.F., R.J. Essig, and O.R. Sarnelle. 1978. Biological investigation of the alewife population, Parker River, Massachusetts. Mass. 89-304 Rep. Proj. No. AFC 16, 31 p.

Collins, G.B. 1952. Factors affecting the orientation of migrating anadromous fishes. U.S. Fish and Wildl. Serv. Fish. Bull. 73:373-396.

Collins, G.B. and C.H. Elling. 1960. Fishway research at the fisheries-engineering research laboratory. U.S. Fish and Wildl. Serv. Circ. 98. 17 p.

Collins, G.B., J.R. Gauley, and C.H. Elling. 1962. Ability of salmonids to ascend high fishways. Trans. Am. Fish. Soc. 91:1-7.

Cooper, J.C. (ed.). 1984. Proceedings of a workshop on critical data needs for shad research on Atlantic Coast of North America. Hudson River Found. Sci. Environ. Res. Rep., 70 p.

Corbett, H.R. 1977. Virginia White Water. Seneca Press, Springfield, Va., 289 p.

Cridlin, W.B. 1923. A history of Colonial Virginia. Williams Printing Co., Richmond, Va., 181 p.

Dane, B.G. 1978. A review and resolution of fish passage problems at culvert sites in British Columbia. Fish and Mar. Serv. Tech. Rep. 810, 126 p.

Dass, P. 1970. Analysis of slot orifice fishways. M.S. Thesis, Univ. of Idaho, Moscow, 101 p.

Decker, L.F. 1967. Fishways in Maine. Maine Dep. Inland Fish. and Game, Augusta, Maine, 47 p.

Dodson, J.J. and W.C. Leggett. 1974. Role of olfaction and vision in the behavior of American shad (Alosa sapidissima) homing to the Connecticut River from Long Island Sound. J. Fish. Res. Bd. Can. 31:1607-1619.

Dominy, C.L. 1971. Changes in blood lactic acid concentrations in alewives (Alosa pseudoharengus) during passage through a pool and weir fishway. J. Fish. Res. Bd. Can. 28:1215-1217.

Dominy, C.L. 1973. Effect of entrance-pool weir elevation and fish density on passage of alewives (Alosa pseudoharengus) in a pool and weir fishway. Trans. Am. Fish. Soc. 102:398-404.

Dow, R.L. 1962. Swimming speed of the river herring (Pomolobus pseudoharengus) J. du Conseil, 27:77-80.

Downman, R.H. 1883. Shad, herring, etc., excluded from the Rappahannock River by dams. U.S. Fish Comm. Bull. 3:392.

Dryden, R.L. and C.S. Jessop. 1974. Impact analysis of the Dempster highway culvert on the physical environment and fish resources of Frog Creek. Fish and Mar. Serv., Can. Dep. Environ./Fish. Oper. Dir./ Cent. Reg./ Tech. Rep. Ser. CEN/T-74-5, 59 p.

Dryden, R.L. and J.N. Stein. 1975. Guidelines for the protection of the fish resources of the Northwest Territories during highway construction and operation. Fish. and Mar. Serv., Can. Dep. Environ./Fish. Oper. Dir./Cent. Reg./Tech. Rep. Ser. CEN/T-75-1. 32 p.

Dudley, R.G., A.W. Mullis, and J.W. Terrell. 1977. Movements of adult striped bass (Morone saxatilis) in the Savannah River, Georgia. Trans. Am. Fish. Soc. 106:314-322.

Engel, P. 1974. Fish passage facilities for culverts of the Mackenzie Highway. Dep. Environ., Hydraul. Div., Can. Cent. Inland Waters, Burlington, Ont., 33 p.

Evans, W.A. and F.B. Johnston. 1980. Fish migration and fish passage: a practical guide to solving fish passage problems. USDA For. Serv. Reg. 5, 88 p.

Everhart, W.H., A.W. Eipper, and W.D. Youngs. 1975. Principles of fishery science. Cornell Univ. Press, Ithaca, N.Y., 288 p.

Federal Energy Regulatory Commission. 1981. Water resources appraisal for hydroelectric licensing: Upper James River Basin, Virginia. Office of Electric Power Regulation, Atlanta Regional Office, FERC-0085, 53 p.

Fisk, L.O. 1959. Experiments with a vertical baffle fishway. Calif. Fish and Game 45(2):111-122.

Foote, P.S. 1976a. Blood lactic acid levels and mortality of American shad (Alosa sapidissima) utilizing the Holyoke Dam fishlift, Massachusetts, 1974 and 1975. Pages 261-284 in Proc. Workshop on American shad, 14-16 Dec. 1976, Amherst, Mass.

Foote, P.S. 1976b. Blood lactic acid levels and age structure of American shad (Alosa sapidissima) utilizing the Holyoke Dam fishlift, Massachusetts, 1974 and 1975. M.S. thesis, Univ. of Massachusetts, Amherst, Mass. 97 p.

Gauley, J.R. 1966. Effects of water velocity on passage of salmonids in a transportation channel. Fish. Bull. 66:59-63.

Gauley, J.R. and C.S. Thompson. 1962. Further studies on fishway slope and its effect on rate of passage of salmonids. Fish. Bull. 63:45-62.

Gauley, J.R., C.R. Weaver, and C.S. Thompson. 1966. Research on fishway problems, May 1960 to April 1965. 3rd Prog. Rep. Fish. Engin. Res. Prog., Corps. Engin., North Pac. Div., Portland, Ore., p 29-66.

Gebhards, S., and J. Fisher. 1972. Fish passage and culvert installations. Idaho Fish and Game Rep., 12 p.

Glebe, B.D. and W.C. Leggett. 1981a. Temporal, intra-population differences in energy allocation and use by American shad (Alosa sapidissima) during the spawning migration. Can. J. Fish. Aquat. Sci. 38:795-805.

Glebe, B.D. and W.C. Leggett. 1981b. Latitudinal differences in energy allocation and use during the freshwater migrations of American shad (Alosa sapidissima) and their life history consequences. Can. J. Fish. Aquat. Sci. 38:806-820.

Glover, T. 1676. An account of Virginia. Philos. Trans. Royal Soc. Vol. X, No. 126.

Harrison, M.B. 1972. Analysis of a skewed slot-orifice. M.S. Thesis. Univ. of Idaho, Moscow. 89 p.

Hening, W.H. 1820. Statutes at large, Laws of Virginia. Franklin Press, 1969 Reprint, Vol. 7.

Henry, S.M. 1976. Development of fish passage facilities for American shad at Holyoke Dam on the Connecticut River. Pages 289-303 in Proceedings of a workshop U.S. Fish and Wildlife Service, Newton Corner, Massachusetts, and U.S. National Marine Fisheries Service, Gloucester, Massachusetts, 350 p.

Jones, D.R., J.W. Kiceniuk, and O.S. Banford. 1974. Evaluation of the swimming performance of several fish species from the Mackenzie River. J. Fish. Res. Bd. Can. 31:1641-1647.

Jones, F.R.H. 1968. Fish Migration. Edward Arnold Publ. Ltd., London, 325 p.

Jordan, D.S. 1889. Report of explorations made during the summer and autumn of 1888, in the Alleghany region of Virginia, North Carolina, and Tennessee, and in western Indiana, with an account of the fishes found in each of the river basins of those regions. Bull. U.S. Fish Comm. 7:97-173.

Katopodis, C., P.R. Robinson, and B.G. Sutherland. 1978. A study of model and prototype culvert baffling for fish passage. Can. Fish. and Mar. Serv. Tech. Rep. 828. 78 p.

Katz, H.M. 1972. Migration and behavior of adult American shad, Alosa sapidissima (Wilson), in the Connecticut River, Massachusetts. M.S. Thesis, Univ. of Massachusetts, Amherst, Mass. 97 p.

Katz, H.M. 1976. Circadian rhythms, migration, and spawning related behavior of the American shad, Alosa sapidissima (Wilson). Ph.D. Dissertation, University of Massachusetts, Amherst, Mass. 212 p.

Kay, A.R., and R.B. Lewis. 1970. Passage of anadromous fish through highway drainage structures. Calif. Div. Highways, Dist. 01 Res. Rep. 629110, 15 p.

Kerr, J.E. 1953. Studies on fish preservation at the Contra Costa steam plant of the Pacific Gas and Electric Company. Calif. Fish and Game, Fish Bull. No. 92, pages 20-35.

Lauman, J.E. 1976. Salmonid passage at stream-road crossings: a report with department standards for passage of salmonids. Ore. Dep. Fish. and Wildl., Portland. 78 p.

Layzer, J.B. 1974. Spawning sites and behavior of American shad Alosa sapidissima (Wilson), in the Connecticut River between Holyoke and Turner Falls, Massachusetts, 1972. M.S. Thesis, Univ. of Massachusetts, Amherst, Mass. 46 p.

Layzer, J.B. 1979. Transportation of adult American shad past dams on the Connecticut River, Massachusetts, 1973-76. Prog. Fish-Cult. 41:7-9.

Leedy, D.L., T.M. Franklin, and E.C. Hekimian. 1975. Highway-wildlife relationships, vol 2. An annotated bibliography. U.S. Dep. Trans., Fed. Highway Admin. Tech. Rep. FHWA-RD-76-5, 417 p.

Leggett, W.C. 1976. The American shad (Alosa sapidissima), with special reference to its migration and population dynamics in the Connecticut River. Pages 169-226 in D. Merriman and L.M. Thorpe, eds. The Connecticut River Ecological Study. American Fisheries Society Monograph I. 252 p.

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

Leim, A.H. 1924. The life history of the shad, Alosa sapidissima (Wilson), with special reference to factors limiting its abundance. Contrib. Can. Biol. N.S. 2(11):161-284.

Libey, G.S. 1976. A mathematical model and computer simulation of the anadromous alewife, Alosa pseudoharengus (Wilson), migration in the Parker River, Massachusetts. Ph.D. Dissertation, Univ. of Massachusetts, Amherst, Mass. 196 p.

Loesch, J.G., and W.A. Lund, Jr. 1977. A contribution to the life history of the blueback herring, Alosa aestivalis. Trans. Am. Fish. Soc. 106:583-589.

Long, C.W. 1959. Passage of salmonids through a darkened fishway. USFWS Spec. Sci. Rep. Fish. 300, Washington D.C. 9 p.

Lowman, B.J. 1974. Investigation of fish passage problems through culverts. USDA For. Serv. Equip. Dev. Cent., Proj. Rec. ED&T 2427, Missoula, Mont. 17 p.

Mayo, R.K. 1974. Population structure, movement, and fecundity of the anadromous alewife, Alosa pseudoharengus (Wilson, in the Parker River, Massachusetts, 1971-72. M.S. Thesis, Univ. of Massachusetts, Amherst, Mass., 118 p.

Metsker, H.E. 1970. Fish versus culverts. USDA For. Serv. Eng. Tech. Rep. ETR-7700-5, Washington D.C., 19 p.

Middleton, A.P. 1953. Tobacco coast. The Mariners Museum, Newport News, Va. Whittlet and Shepperson, Richmond, Va. 482 p.

Miller, J.P., F.R. Griffiths, and P.A. Thurston-Rogers. 1982. The American shad (Alosa sapidissima) in the Delaware River Basin. Prepared for Delaware Basin Fish and Wildl. Mgmt. Coop. 132 p.

Ministry of Environment. 1980. Stream enhancement guide. Prov. of B.C., Govt. of Can. 96 p.

Moffitt, C.M., B. Kynard, and S.G. Rideout. 1982. Fish passage facilities and anadromous fish restoration in the Connecticut River basin. Fisheries 7:2-11.

Nichols, P.R. 1958. Effects of New Jersey - New York pound-net catches on shad runs of Hudson and Connecticut Rivers. Fish. Bull. 58:491-500.

Nichols, P.R., and D.E. Louder. 1970. Upstream passage of anadromous fish through navigation locks and use of the stream for spawning and nursery habitat Cape Fear River, N.C., 1962-66. U.S. Fish and Wildl. Serv. Circ. 352, 12p.

Oatis, P.H. 1972. Connecticut River shad study- evaluation of Holyoke fishlift. Mass. Div. Fish and Game, Job Prog. Rep. AFS-4, 9:4p.

Otis, M.B., and D.G. Pasko. 1964. Suggested measures for minimizing damage to fishing streams from highway projects. N.Y. State Conserv. Dep., Div. Fish and Game, Bur. Fish, 4 p.

Pearson, J.C. 1942. The fish and fisheries of Colonial Virginia. William and Mary Quarterly 22(second series):213-220.

Radtke, L.D. and J.L. Turner. 1967. High concentrations of total dissolved solids block spawning migration of striped bass, Morone saxatilis, in the San Joaquin River, California. Trans. Am. Fish. Soc. 96:405-407.

Richkus, W.A. and G. DiNardo. 1984. Current status and biological characteristics of the alosid stocks of the eastern United States: American shad, hickory shad, alewife, and blueback herring. Atlantic States Marine Fisheries Commission, Fisheries Management Report 4, Washington D.C. 225 p.

Rizzo, B. 1968. Fish passage facilities design parameters for Connecticut River dams, Holyoke Dam. Tech. Comm. Fish. Mgmt. Connecticut River Basin. 21 p.

Rizzo, B. 1983. Preliminary report on the feasibility of constructing fish passage facilities at dams on the James River in Richmond, Virginia. Appendix I in Atran, et al. op cit, 27 p.

Rockfish Corporation. 1981. Virginia hydro dam survey. Prepared for U.S. Dep. of Energy, Region III, Va. State Office of Emergency and Energy Services, 3 vol.

Saila, S.B., T.T. Polgar, D.J. Sheehy, and J.M. Flowers. 1972. Correlations between alewife activity and environmental variables at a fishway. Trans. Am. Fish. Soc. 101:583-594.

Saunders, P., B. Kynard, and R.J. Reed. 1980. Biology of American shad utilizing the Holyoke Dam fishlifts, Connecticut River, Massachusetts in 1979. Final Report to Northeast Utility Service Company, Mass. Coop. Fish. Res. Unit. 15 p.

Scherer, M.D. 1974. Analysis of factors affecting passage of American shad, (Alosa sapidissima, Wilson) at Holyoke Dam, Massachusetts, and assessment of juvenile growth and distribution above the dam. Ph.D. Dissertation, Univ. of Massachusetts, Amherst, Mass., 245 p.

Sheridan, W.L. 1969. Benefit/cost aspects of salmon habitat improvement in the Alaska region. USDA For. Serv., Reg. 10, Juneau, 47 p.

Shoemaker, R.H. 1956. Hydraulics of box culverts with fish-ladder baffles. Nat. Res. Council, Highway Res. Bd. Proc. 35:196-209.

Slatick, E. 1970. Passage of adult salmon and trout through pipes. U.S. Fish and Wildl. Serv. Spec. Sci. Rep. Fish. 592, 18 p.

Slatick, E. 1971. Passage of adult salmon and trout through an inclined pipe. Trans. Am. Fish. Soc. 100:448-455.

Slatick, E. 1975. Laboratory evaluation of a Denil-type steeppass fishway with various entrance and exit conditions for passage of adult salmonids and American shad. Mar. Fish. Rev. 37(9):17-26.

Stevenson, C.H. 1897. The restricted inland range of shad due to artificial obstructions and its effect on natural reproduction. Bull. U.S. Fish Comm. 17:265-271.

Stevenson, C.H. 1899. The shad fisheries of the Atlantic coast of the United States. U.S. Comm. Fish Fish., pt. 24, Rep. Comm. 1898: 101-269.

Sykes, J.E. 1951. The transfer of adult shad. Prog. Fish-Cult. 13:45-46.

Thoreau, H.D. 1837. A week on the Concord and Merrimack Rivers, C.F. Hovde (ed.). Princeton Univ. Press, 1980, 612 p.

Virginia Fish Commission. 1875. Annual report for 1875. Richmond, Va. 38 p.

Walburg, C.H. 1952. Experimental transportation of live shad past Susquehanna dams. U.S. Fish and Wildl. Serv. Spec. Sci. Rep. Fish. 114, 13 p.

Walburg, C.H. and P.R. Nichols. 1967. Biology and Management of the American shad and status of the fisheries, Atlantic coast of the United States, 1960. U.S.D.I. Spec. Sci. Rep. No. 550, 105 p.

Warner, J.P. 1983. Demography, food habits and movements of striped bass (Morone saxatilis, Walbaum) in the Connecticut River, Massachusetts. M.S. Thesis, Univ. of Massachusetts, Amherst, Mass., 94 p.

Watson, J.F. 1968. The early life history of the American shad, Alosa sapidissima (Wilson), in the Connecticut River above Holyoke, Massachusetts. M.S. Thesis, Univ. of Massachusetts, Amherst, Mass. 55 p.

Watts, F.J. 1974. Design of culvert fishways. Water Resour. Res. Inst., Univ. Idaho, Moscow. 62 p.

Watts, F.J., P. Dass. C.P. Liou, and M. Harrison. 1972. Investigation of culverts and hydraulic structures used for fishways and the enhancement of fish habitat. Water Resour. Res. Inst., Univ. Idaho, Tech. Rep. 7 p.

Weaver, C.R. 1965. Observations on the swimming ability of adult American shad (Alosa sapidissima). Trans. Am. Fish. Soc. 94:382-385.

Wharton, J. 1957. The bounty of the Chesapeake. Virginia 350th Anniv. Celebration Corp., Williamsburg, Va. 78 p.

White, J.C., Jr., J.B. Bailey, and M.L. Brehmer. 1984. Striped bass: did the James River love bug ever bite above the fall line. Presented at the Fall meeting of the Atlantic Estuarine Research Society, 11-13 October 1984, Salisbury, Md.

Wilstach, P. 1929. Tidewater Virginia. The Bobbs-Merrill Co., Indianapolis, In. 326 p.

Woolcott, W.S. 1985. James River fisheries and thermal effects. Va. J. Sci. 36(1):26-29.

Wooley, C.M. and E.J. Crateau. 1983. Biology, population estimates, and movement of native and introduced striped bass, Apalachicola River, Florida. N. Am. J. Fish. Mgmt. 3:383-394.