Diadromous Fish Passage: A Primer on Technology, Planning, and Design for the Atlantic and Gulf Coasts

U.S. Department of Commerce | National Oceanic and Atmospheric Administration | National Marine Fisheries Service

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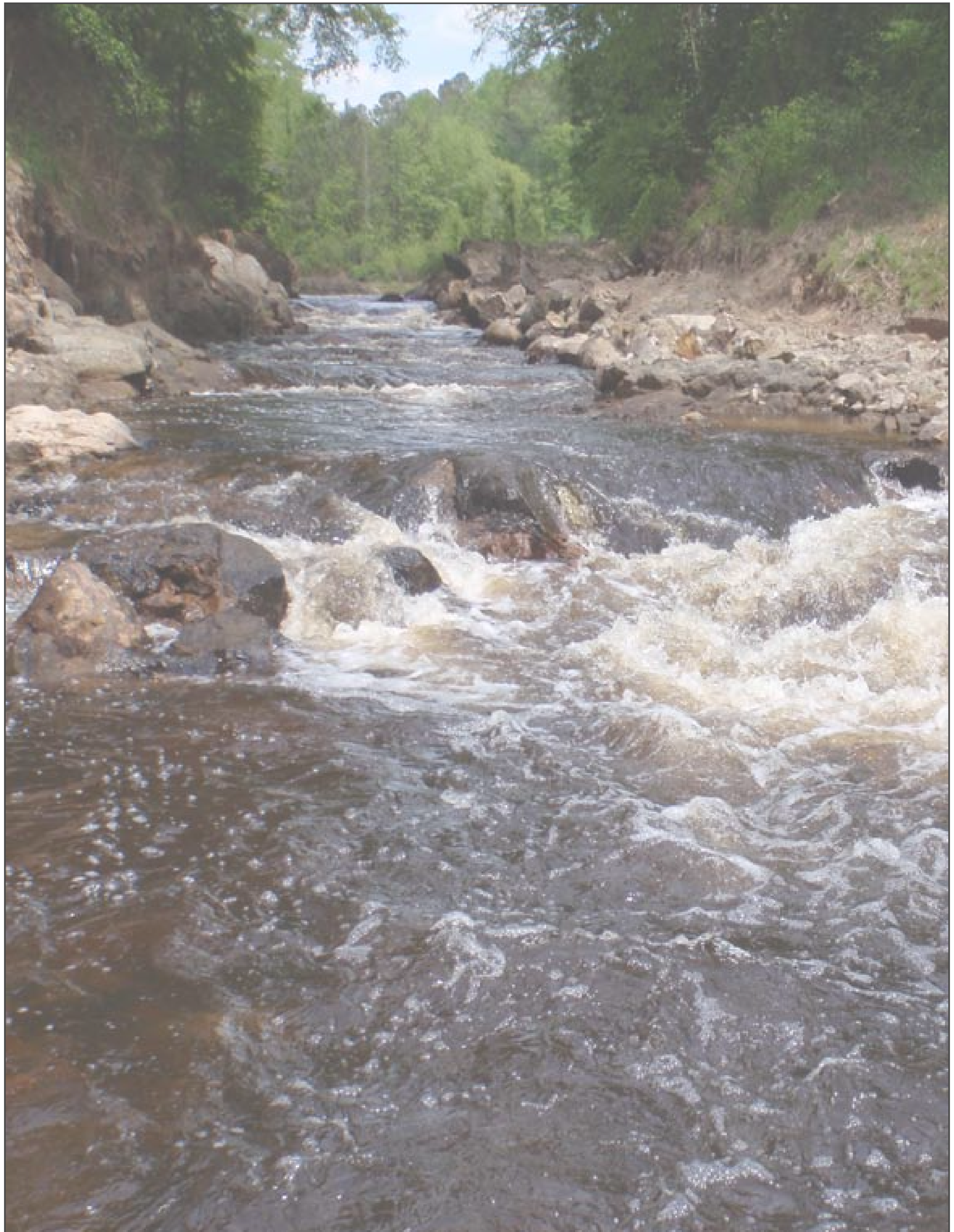

ACRONYMS AND ABBREVIATIONS

AWS	Auxiliary Water System
ASMFC	Atlantic States Marine Fisheries Commission
CFD	Computational Fluid Dynamics
Cfs/cfs	Cubic feet per second, ft^3 s
DPS	Distinct Population Segment
EPRI	Electric Power Research Institute
ESA	Endangered Species Act
FAO	Food and Agriculture Organization of the United Nations
FERC	Federal Energy Regulatory Commission
FHA	Federal Highway Administration
FPA	Federal Power Act
GSMFC	Gulf States Marine Fisheries Commission
NMFS	National Marine Fisheries Service
O&M Plan	Operations and Maintenance Plan
PIT	Passive Integrated Transponder
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
TL	Total length
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey

FOREWORD

The U.S. Department of Commerce, National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS), is responsible for conservation, management, and protection of America's living marine resources throughout U.S. river basins in coordination with other state and federal agencies, local governments, Indian tribes, fisheries commissions, commercial and recreational fishers, and conservation organizations. NMFS' authority to manage marine fish in these river basins comes from Congress. Specifically, Congress has directed NMFS to manage marine species in river basins, including a grant of discretionary authority to the agency to order fish passage at licensed dams licensed by the Federal Energy Regulatory Commission. NMFS' Congressionally mandated, statutory authorities include the Federal Power Act, the Endangered Species Act, the Magnuson-Stevens Fishery Conservation and Management Act, the Anadromous Fish Conservation Act, and the Fish and Wildlife Coordination Act.

Sea-run migratory *anadromous* fish are important living marine fishery resources of the Atlantic and Gulf coasts that spend part of their lives in ocean waters yet must ascend to estuarine and freshwater rivers to spawn and complete their life cycles. Anadromous fish of tremendous economic and ecological importance on the Atlantic and Gulf coasts include but are not limited to American shad, river herring, Alabama shad, and other alosines; striped bass; Gulf, Atlantic, and shortnose sturgeon; Atlantic salmon; sea-run brook trout; and rainbow smelt. Another sea-run migratory species of ecological and economic importance is the American eel. The *catadromous* American eel spends its juvenile and adult life in estuarine and freshwater habitats, it then migrates to the Sargasso Sea in the North Atlantic Ocean to spawn and die. Tiny progeny of American eels, called glass eels or elvers, follow ocean currents to return to river basins on both sides of the North Atlantic to grow to adulthood. Collectively, anadromous and catadromous species are often referred to as *diadromous* fishes.

Diadromous fish travel great distances between the ocean and rivers to complete their life cycles. For example, American shad and river herring migrate through many ecological regions and human jurisdictions, ascending river basins hundreds of miles from the ocean to reach spawning grounds in the Appalachian foothills, Piedmont, and Coastal Plain physiographic regions. Juvenile shad and blueback herring from the St. Johns River in Florida, the southerly limit of their present distribution, migrate as much as 1,500 miles following the Gulf Stream to their adult rearing grounds in the plankton-rich waters of the North Atlantic off Nova Scotia and the Gulf of Maine. Other migratory diadromous species migrate between ocean or estuarine waters and freshwater rivers, for distances that vary by species. This migration is often hampered by anthropogenic activities that alter the waterways on which diadromous fish rely. Dams have been identified as a significant source of impacts on these diadromous species (ASMFC 2000; 2009; Fay et al. 2006).

Dams and other barriers (including hydroelectric dams, flood control dams, water supply and irrigation diversion structures, impassable roadway culverts, etc.) affect fish migrations in many ways. They impede or totally block upstream migrations, reducing access to spawning, feeding, and maturation habitats. Dams often create large reservoirs inundating former spawning areas and presenting additional barriers to upstream and downstream migrations even when passage is installed. Dams may also cause problems downstream by decreasing flows or causing harmful fluctuations to flows, causing water quality problems, or changing habitat conditions, such as decreasing amounts of large woody debris and changing gravel size in the river bed. Entrainment of downstream migrant fish through hydropower turbines or water diversion systems may result in excessive mortality unless properly designed screens and bypass facilities are in place. The primary and most important consequence of impassable barriers is decreases in population abundance and production capacity because of reductions in habitat quantity and quality and mortality from interactions with turbines and other structures. Blockage of ocean-river spawning migrations for salmon, the shads and river herring, and sturgeon is one of the important factors resulting in declines in stocks and fisheries and extirpation in many river basins (ASMFC 2000, 2009; Fay et al. 2006). Protection, restoration, and management of diadromous fishes and their riverine habitats is an integral part of NOAA's ecosystem management approach for assuring healthy living marine resources on the east coast of the U.S., including sustainable populations of marine mammals and federally managed finfish (NMFS 2009a).

The impetus for preparation of this fish passage design overview document is the growing recognition that blockage of ocean-river fish migrations by construction of dams during the past two centuries has had multiple effects on riverine, estuarine, and marine ecosystems, wildlife and fisheries in North America. Over 4.2 million dams were constructed since the early 1700s in North America (Graf 2002). Large numbers of those dams were abandoned after they became obsolete, and remain barriers to fish passage. Today removal of obsolete dams is recognized as important for restoration of public natural resources including many aquatic species, fisheries, and recreation. Many dams, however, are considered important for water resource management, flood control, and hydroelectric power production. In recent years, advancements in bioengineering have yielded increasingly effective fish passage designs for diadromous fish, opening a new era in restoration of essential life-cycle migrations; biological diversity; riverine, estuarine and ocean ecosystem health; recovery in numbers and return of diadromous fish to their historic ranges; and sustainable recreational and commercial fisheries.

This document is intended to provide an overview of existing fish passage technology. NMFS hopes that doing so will allow individuals to have a better understanding of agency fish passage considerations in Atlantic and Gulf coast river basins, thus assisting individuals in the planning and development of safe, timely, and effective fish passage in the future.

NMFS acknowledges, however, that not all sites are alike. Dams and river basins can present unique and novel resource and engineering issues. Further, special consideration may be needed where projects potentially impact species protected under the Endangered Species Act, including formal statutory consultation between NMFS and the federal agency granting the permit or license at the project. Accordingly, NMFS does not intend this overview document to provide definitive guidelines and answers to all fish passage questions at a particular dam, and individuals should not consider this document as establishing rules or regulations or policy or procedure. Each site must be examined and reviewed on a case-by-case basis.

This primer was developed by NMFS' biologists and engineers in collaboration with U.S. Geological Survey (USGS) fish passage research specialists. Ben Rizzo and Dick Quinn provided substantial information by way of project examples, design criteria and photographs to facilitate the development of this review. This is a working document and is intended to be periodically updated. Suggested changes, additions, or questions should be directed to Prescott Brownell (Prescott.Brownell@noaa.gov) or Sean McDermott (Sean.McDermott@noaa.gov) for consideration in updating this document. Assistance from NMFS fish passage specialists can be obtained by contacting the Northeast Region Habitat Conservation Division at (978) 281-9102, and the Southeast Region Habitat Conservation Division at (727) 824-5317.

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The Dam Construction Era

River fisheries for ocean-river migratory species provided important food sources for human populations throughout history and provided important components for establishment and growth of many cultures. Rivers provide dependable water sources, travel ways for commerce, and important hydro-mechanical power sources for development of agricultural and industrial technology. As societal and technological development expanded after the medieval period in Europe, North America, and Asia, construction of dams for navigation and hydro-mechanical power spread throughout many river basins and began to impact the migration of culturally important diadromous fish. Over 4.2 million dams were constructed in the continental United States from the 18th Century to the present day (Graf 2002). In the early colonial period, dams were constructed on small rivers and tributaries to power grist mills, and for improvement of river navigation by construction of diversion dams and canal systems to enable river boats to bypass rapids and shoal areas. Later in the mid-1800s the rise of the Industrial Revolution led to construction of larger dams to provide hydro-mechanical power for larger textile and industrial mills. Intense conflicts, often called the "shad wars," arose between dam-building industrialists and commercial fishers from 1780 to the late 1800s (Watson 1996). The rise of hydroelectric power in the 1890s led to a great dam construction rush that resulted in much larger dams on nearly all of the nation's major rivers up to the present day.

Early Development of Fish Passage

As dam construction expanded and historic fisheries declined in Europe and America, conflicts between mill-industrialists and fisheries ensued. In response to declining fisheries, design of fish passage facilities began in France and North America by the 17th Century (McDonald 1887; Rajaratnam and Katopodis 1984). Early fish passages in France consisted of steep, constructed channels "roughed" with bundles of tree branches to dissipate energy and provide passage for some fish species over low-head dams.

In America, conflicts between mill dam owners and fishers in the late 18th Century led to enactment of laws requiring dams to include "fish sluices," or open gaps in dams for boats and fish (Watson 1996). During the mid- to late 1800s, Marshall McDonald of the U.S. Commission of Fish and Fisheries helped develop designs for pool and weir fish ladders for passage of shad at the Augusta Diversion Dam in Georgia and South Carolina, the Columbia Canal Diversion Dam in South Carolina, and other dams on the Atlantic coast (Stevenson 1899). The Augusta fish ladder is still in place (Figures 1-1 and 1-2).

Figure 1-1. Augusta Canal Lock and Dam Fishway, Savannah River, Georgia-South Carolina. Designed by Marshall McDonald, U.S. Commission of Fish and Fisheries, and installed on the Augusta Dam in 1886. *J. Jimenez*

Figure 1-2. View of Augusta Dam depicting alteration of upstream and downstream habitat. The presence of the dam has affected shad populations as noted by Stephenson in 1899.

"The quality of muddy water rendered the lower length of the stream unfavorable for spawning purposes, and the dam near Augusta prevented the utilization of the area above that point, thus limiting the spawning grounds to a few miles just below the Augusta dam, and within this restricted area the eggs allegedly were eaten by the predaceous fish attracted there." —Stephenson (1899)

While McDonald's fish ladder designs were based on his observations of successful passage for salmon, the designs were less effective for Atlantic coast shad, river herring, and other diadromous species. Nonetheless, McDonald's designs provided a foundation for further development of effective fish passage designs. In France, Denil adapted McDonald's early pool and weir design and eventually developed an effective fish ladder around 1910, now called the Denil ladder design (Kamula 2001). Denil initiated the first focused fish passage and hydraulics studies and stimulated research on fish behavior and hydraulics in Europe and the British Isles (Osborn 1987). Fish passage research waned after the early 1900s, but was rejuvenated in the 1970s by researchers and engineers. The American Fisheries Society has held fish passage conferences and published summaries of fish passage innovations (Odeh 1999) and often holds special sessions on fish passage at its annual meeting to share expanding research and innovations on upstream and downstream fish passage and dam removal. Fortunately, recent advances in fish passage technology are resulting in development of practical and effective passage designs for most dams and artificial barriers that are successful in passing important diadromous fish species.

The ecological importance of fish passage for riverine, estuarine, and ocean fisheries, and ocean ecosystem health is increasingly gaining recognition, particularly on the U.S. Atlantic and Gulf coasts.

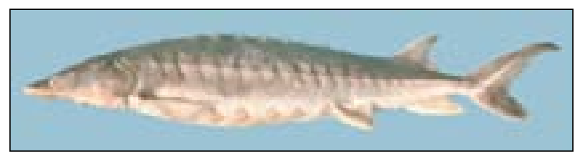
Chapter 2. Diadromous Species

There are many fish and other aquatic species that may be described as ocean-river migratory; all have ecological importance to coastal systems. Of these ocean-river migratory fish, fourteen diadromous species have historic or current importance to commercial and recreational fisheries and are protected or managed; thirteen of the fourteen are anadromous and one (American eel) is catadromous. Restoring fish passage is important not only for popular recreational and commercially important species, but for virtually all indigenous aquatic species. Because these fishes utilize both coastal and inland habitat during portions of their life history, they are particularly vulnerable to various threats such as poor water quality, altered habitat, overfishing, and blocked migratory pathways. Populations of several species are at all-time lows (Greene et al. 2009); populations or subspecies of four are listed under the Endangered Species Act (ESA) as threatened or endangered , three others have been petitioned for listing, while two others are being considered for listing. Conversely, after experiencing major declines from the 1800s through the 1980s, stocks of striped bass (*Morone saxatilis*) are considered restored (ASMFC 2003). The species are arranged below in phylogenetic order.

Figure 2-1. Sea lamprey *Petromyzon marinus*

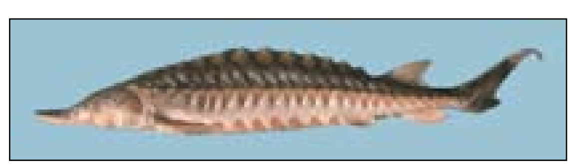
The sea lamprey ranges along the Atlantic Coast of North America from Florida to Labrador, and across the North Atlantic to the British Isles and Europe. Natural landlocked populations occur in several New York lakes and in recent years have moved into the Great Lakes. Although not well-studied throughout its range, researchers in the Northeast are concerned about the status of sea lamprey because of its ecological role in marine, estuarine, and riverine food webs (Kircheis 2004; Nislow and Kynard 2009). The Connecticut River population appears to be stable based on counts at the Holyoke Dam during the past 20 years (USFWS 2007). However, other sea lamprey stocks have declined (Renaud 1997) and are likely affected by siltation, pollution, dams, water withdrawals and other anthropogenic activities throughout their range. Currently the sea lamprey is not a state or federally managed species; management activities to limit population numbers are occurring where lamprey are invasive or considered a nuisance species (Christie and Goddard 2003; Kircheis 2004; Nislow and Kynard 2009).

Figure 2-2. Shortnose sturgeon *Acipenser brevirostrum*



This species occurs along the Atlantic Coast from the Saint John River in New Brunswick, Canada, to the St. Johns River in Florida. Two partially landlocked populations are known: Santee River in South Carolina and the Holyoke Pool section of the Connecticut River (Dadswell et al. 1984). Shortnose sturgeon have been federally listed as an endangered species under the ESA since 1973. Shortnose sturgeon are considered amphidromous (i.e., they move between the fresh and estuarine areas of a river) and do not have a marine-dependent life stage. Shortnose sturgeon seek spawning habitat in the Fall Line zone located between the Coastal Plain and the Piedmont; this zone is farther upstream in rivers within the southern U.S. compared to the northern U.S.

Figure 2-3. Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*



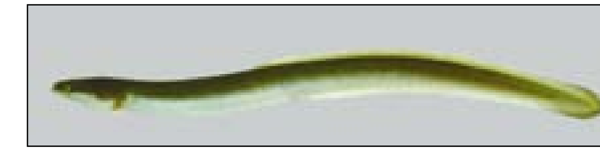
The Atlantic sturgeon is found on the Atlantic Coast from Labrador through northern Florida. Historically, important sturgeon fisheries existed in nearly all Piedmont river basins.

Due to a variety of impacts, including river impoundments, water quality deterioration, bycatch, and overfishing, Atlantic sturgeon have declined to historically low levels (Atlantic Sturgeon Status Review Team 2007). Five Distinct Population Segments of Atlantic sturgeon have been identified (Atlantic Sturgeon Status Review Team 2007) and NMFS has listed each DPS under the ESA (75 FR 61872). Atlantic sturgeon move from the estuary to the marine habitat as juveniles grow; they return to their natal rivers to spawn. In New England and Mid-Atlantic river basins, Atlantic sturgeon may spawn from the head of the tide to locations well upriver, until blocked by dams. In the South, Atlantic sturgeon can ascend hundreds of miles above the head of the tide to spawn. Historical accounts describe large sturgeon movements and Native American harvests well above the Fall Line in the Savannah and Pee Dee river basins (Lawson 1709).

Figure 2-4. Gulf sturgeon *Acipenser oxyrinchus desotoi*

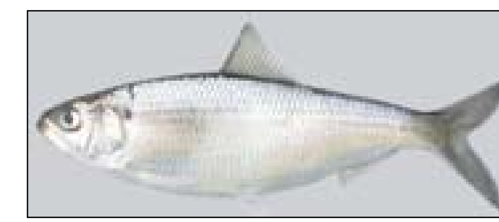
A geographically isolated subspecies of the Atlantic sturgeon, the Gulf sturgeon inhabits the Gulf of Mexico and rivers between Louisiana to Florida. Gulf sturgeon enter the rivers for spawning in the spring and then, cued by dropping water temperatures, overwinter in the Gulf of Mexico. Gulf sturgeon were listed as threatened under the ESA in 1991 (56 FR 49653) given a decline due to overfishing, dam construction, and habitat degradation. Critical habitat has been designated based on 7 reproducing riverine populations and adjacent marine areas (68 FR 13370). Estimates of riverine population size vary by location and method (USFWS and NMFS 2009); generally, the Suwanee River population appears to be slowly increasing.

Figure 2-5. American eel *Anguilla rostrata*



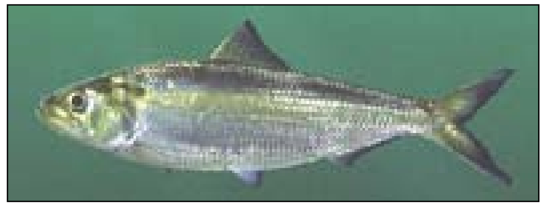
The American eel is the sole catadromous species in the priority group. It ranges from southern Greenland to northeastern South America. The American eel is ubiquitous in many habitats and can contribute to more than 25% of the total fish biomass in some individual systems (Ogden 1970). Many studies have indicated that American eel populations are declining (Haro et al. 2000). Fishing pressure and habitat loss, such as by blockages, are implicated as contributing factors in the decline (Greene et al. 2009). U.S. Fish and Wildlife petitioned in 2011 to list this species as threatened under the ESA.

Figure 2-6. Blueback herring *Alosa aestivalis*



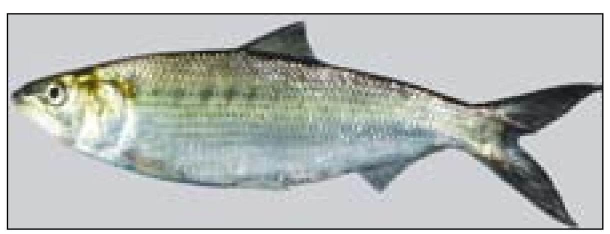
The blueback herring ranges from Cape Breton, Nova Scotia, to the St. Johns River in Florida; landlocked populations are known to exist in some river basins. This species is often lumped with the alewife into the collective term “river herring.” NMFS identified river herring as species of concern in 2006 (NMFS 2009b) and in 2011, NMFS was petitioned to list it as threatened under the ESA. All members of the genus *Alosa* are collectively referred to as “alosines.” In response to severe declines in population abundance, five states—Massachusetts, Rhode Island, Connecticut, Virginia, and North Carolina—have implemented moratoria on the harvest of river herring (ASMFC 2009); however the moratorium in Virginia only includes waters that flow into North Carolina. The blockage of spawning rivers by dams and other impediments, combined with the degradation of water quality, has severely depleted the amount of suitable spawning habitat. Fishing pressure is also known to reduce abundance of blueback herring.

Figure 2-7. Alabama shad *Alosa alabamae*



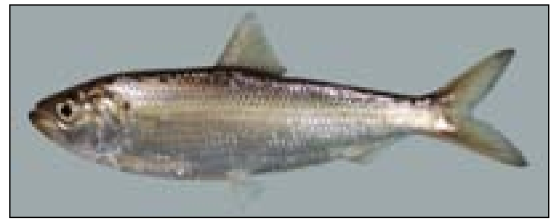
Once widely distributed throughout the Gulf Coast and central United States, the range of Alabama shad is currently more limited (Ely et al. 2008). The largest remaining population probably occurs in the Apalachicola River, Florida, below the Jim Woodruff Lock and Dam. Outside Florida, spawning populations may still persist in Choctawhatchee and Conecuh rivers in Alabama; Pascagoula River in Mississippi; Ouachita River in Arkansas; and the Missouri, Gasconade, Osage, and Meramec rivers in Missouri. It was identified as a Species of Concern in 1997 by NMFS. Factors for declines include locks and dams blocking habitat access, habitat and thermal alterations, poor water quality, siltation, dredging, and bycatch (NMFS 2008a). While population sizes are much lower than historical levels, recent reports show small increases in some populations likely due to increased passage frequency at a few locations.

Figure 2-8. Hickory shad *Alosa mediocris*



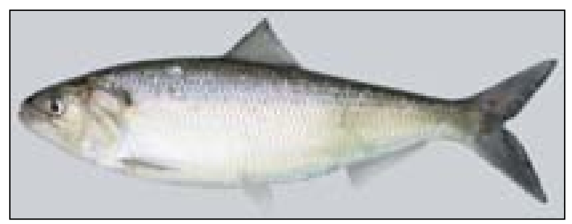
The current range of hickory shad is Cape Cod, Massachusetts, to the St. Johns River, Florida. The greatest abundance appears to be in Albemarle Sound, North Carolina, and in the Chesapeake Bay and its tributaries (Greene et al. 2009). Less is known about this species than the other alosines, including habitat requirements for all life stages and migratory behavior.

Figure 2-9. Alewife *Alosa pseudoharengus*



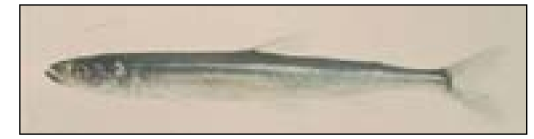
The other member of the river herring group, the alewife occurs from Red Bay, Labrador, to South Carolina. Alewife spawning runs tend to extend further upstream than do blueback herring, and may be more adversely affected by dam blockage. In 2011 NMFS was petitioned to list this species as threatened under the ESA. Refer to the discussion of blueback herring for more information about the decline of alewife.

Figure 2-10. American shad *Alosa sapidissima*



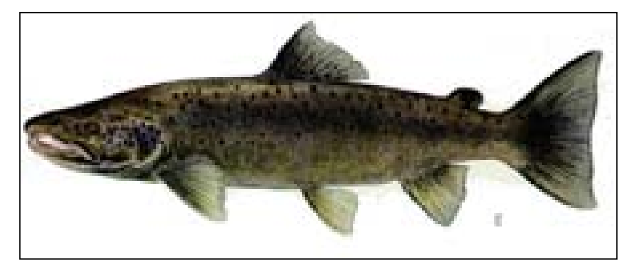
The present range of the American shad extends from St. Lawrence River in Canada to the St. Johns River in Florida. American shad was introduced into several Pacific Coast rivers in the 1870s and has greatly expanded its range on the west coast. Along the Atlantic Coast, most American shad stocks have been in decline because of overfishing, habitat loss due to dams, and upland development (ASMFC 2009, 2010). However, some stocks, such as in the Connecticut River, Pawcatuck River in Rhode Island, and the Santee River in South Carolina, while substantially reduced from historic levels, have stabilized or increased (Greene et al. 2009), likely due to installation of fish passage and restoration of access to historical spawning habitats.

Figure 2-11. Rainbow smelt *Osmerus mordax*



The rainbow smelt naturally occurs along the coastal areas of northeastern North America from Newfoundland to the lower Delaware River but is most abundant from the southern Maritime Provinces south to Massachusetts; records from Virginia are erroneous (Jenkins and Burkhead 1994; MDFG 2006). It has been successfully introduced into freshwater systems in the northeastern and central U.S. (Buckley 1989). Rainbow smelt was identified by NMFS in 2004 as a Species of Concern because of overall declines in the population (NMFS 2007). Factors for these declines include acid precipitation, dams and blocked culverts, spawning habitat degradation, and fishing pressure.

Figure 2-12. Atlantic salmon *Salmo salar*

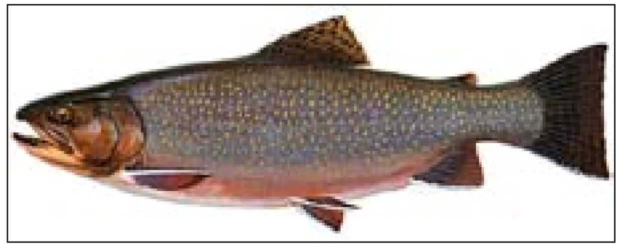


The Atlantic salmon historically ranged from rivers of Ungava Bay in Canada to rivers of Long Island Sound. Because of overfishing and industrial and agricultural activities, most native New England populations of Atlantic salmon have been extirpated and the only remnant native populations persist in Maine. Four DPSs are recognized: 1) Long Island Sound DPS; 2) Central New England DPS; 3) Gulf of Maine DPS and 4) the Outer Bay of Fundy SFA. The two southern segments were extirpated in the 1800s. In 2000, Atlantic salmon were listed as endangered under the ESA. Restoration and rehabilitation efforts through fish stocking and fish passage construction are underway in a number of New England rivers (Kocik and Sheehan 2006).

Conservation hatcheries produce fish from remnant local stocks within a DPS and stock them back into that DPS (Gulf of Maine DPS) while restoration hatcheries produce salmon from brood stock established from donor populations outside their DPS (all other New England hatcheries). All stocks are at very low levels and most are still dependent on hatchery production.

The Gulf of Maine DPS, as identified in 2000, included the naturally reproducing rivers downstream of the former Edwards Dam on the Kennebec River to the St. Croix River, including the Penobscot River up to the old Bangor Dam site. In 2009, NMFS and the U.S. Fish and Wildlife Service (USFWS), collectively the "Services," acted on new information that resulted in an expansion of the range of the Gulf of Maine DPS. The Services determined that naturally spawned and conservation hatchery populations of anadromous Atlantic salmon, whose freshwater range occurs in the watersheds from the Androscoggin River northward along the Maine coast to the Dennys River, including those that were already listed in November 2000, constitute a DPS. This Gulf of Maine DPS was then listed as endangered under the ESA. This expansion includes waters above the former dam sites on the Kennebec and Penobscot Rivers.

Figure 2-13. Sea-Run brook trout *Salvelinus fontinalis*



Historically, sea-run brook trout ranged from Labrador, Canada, to Long Island, New York. Currently, populations exist only in 10 streams in Rhode Island, 5 in Massachusetts, and 65 in Maine (Halliwell 2009). Annett (2005) found that populations of sea-run brook trout in coastal Cape Cod streams were genetically unique to each stream with very low gene flow between adjacent streams. Factors for decline throughout its range include dams and other blockages and loss of habitat, especially through conversion of forest land into cranberry and agricultural fields. Native brook trout are also present in Southern Appalachian Mountain rivers and streams; however they cannot descend rivers to the ocean because of down-river water temperatures exceeding their thermal tolerance during most of the year. It is possible that sea-run brook trout may have been present in southern rivers during and after the last ice age when riverine habitat temperatures were cooler.

Figure 2-14. Striped bass *Morone saxatilis*

Along the Atlantic coast, the striped bass ranges from the St. Lawrence River, Canada, to the St. Johns River, Florida. A separate race occurs in the Gulf of Mexico from the Suwannee River, Florida, west to Texas (GSMFC 2006). Striped bas inhabit coastal waters and are commonly found in bays but enter rivers in the spring to spawn. Striped bass in the Gulf of Mexico were nearly extirpated by the mid-1960s except for remnant populations in the Apalachicola-Chattahoochee-Flint and Mobile-Alabama-Tombigbee river systems of Alabama, Georgia, and Florida due to dam construction and altered environmental conditions (Greene et al. 2009). Later in the 1980s, overfishing and poor environmental conditions led to the collapse of the Atlantic coastal fishery. After undergoing intense management, including a moratorium on harvest, the Atlantic coastal migratory stock of striped bass is now considered to be rebuilt by the Atlantic States Marine Fisheries Commission (ASMFC 2003); however, populations in southern Atlantic coast rivers are still at low levels. Extensive stocking of striped bass continues in an effort to restore populations.

Chapter 3. Fish Passage Barriers and Impediments

Barriers or impediments to fish passage include a wide variety of man-made, in-stream structures, and project operations potentially resulting in fish injury, mortality, diversions leading fish into "dead end" channels, and total blockage or delay in upstream or downstream migration. Natural barriers, such as waterfalls and other geological features, may impede upstream fish movements, and in rare cases may be considered for fish passage improvement when suitable habitat for target species exists upstream. Example barriers are shown in Figure 3-1.

Figure 3-1. Examples of common fish passage barriers.

An upstream passage *impediment* can be defined as any structural feature or project operation causing injury, blockage, or delay of juvenile or adult fish migration relative to a natural river setting. A *barrier* is a structural feature or project operation that entirely blocks upstream fish migration during fish migration seasons. Following are examples of artificial impediments and barriers to fish passage that may be mitigated with currently available technology or project operation modifications:

- Permanent, abandoned, or temporary dams that block or impede fish migration.
- *Hydraulic drop* over an artificial instream structure in excess of 1.5 feet (NMFS 2008b).
- River channel flow reductions that do not provide a sufficient "zone of passage" (e.g. sufficient depth, suitable flow characteristics, resting pools, etc.) for target fish species.
- Project flow operations that attract migrant fish to "dead end" impassable routes such as hydropower tailwater, bypassed river reaches below impassable dams, water diversion canals, industrial intake canals, etc.
- Project flow variations that prevent or delay natural upstream fish movement behavior.
- Water diversions that reduce instream flow in natural migration channels.

- Temperature gradients caused by cold or warm water outfalls from a project operation that may interfere with upstream migratory behavior.
- Degraded water quality in riverine migration or spawning habitat reaches.
- Point-source discharges and mixing zones of industrial process water or municipal wastewater, and potential interference with upstream fish migrations.
- Roadway culverts with characteristics that impede upstream fish migration behavior, including abrupt transitions in lighting, hanging culverts, lack of natural benthic substrate, extreme length, small diameter, etc.

Constructing a safe, timely, and effective fish passage facility at a barrier or impediment has been challenging because the natural *ecological flow* and passage characteristics of a site are greatly altered by the barrier. Further, it is difficult to replicate natural conditions and fully compensate for the loss of the former natural passage channel features using fish passage facilities including nature-like fishways. Careful consideration should be given to the recommendations provided in this document during the planning and design of a potential fishway.

Chapter 4. Fish Passage Planning Considerations

The population viability and mobility of ocean-river migratory and resident fish species that would otherwise move to and from different habitats within the river system may diminish substantially, if not completely, due to the effects of dams and other barriers (Fay et al. 2006; ASMFC 1999, 2000). Dams exist in virtually every watershed in the U.S. and continue to obstruct fish passage (Graf 2002). During consideration of potential fish passage and river ecosystem restoration at a dam, stakeholders provide sociological, ecological, and economic factors to be evaluated by the Federal Energy Regulatory Commission (FERC) during the licensing process. Abandoned or obsolete dams often provide an opportunity for complete removal and full restoration of the riverine conditions. Dams considered to be important may provide opportunities for river restoration either through installation of fish passage facilities or dam removal when the regulatory review process determines the economic or ecological importance of restoration exceeds the economic or other social factors associated with the dam.

Fish passage facilities, or *fishways*, that are appropriately designed and operated help mitigate the impact of barriers on fish by providing passage to and from habitats for spawning, rearing, feeding, growth to maturity, dispersion, migration, and seasonal use of habitat. Upstream and downstream fish passage facilities also mitigate entrainment and mortality at hydropower turbines and impingement and entrainment at dead-end water intakes and diversions. Congress recognized the national importance of fish passage by specifically addressing fishways in the 1920 enactment of the Federal Power Act (FPA) and by making fishways mandatory when prescribed by the Departments of Commerce, Interior, or Agriculture. Decades later, Congress reaffirmed the public interest importance of fish passage and provided guidance as to what constitutes a fishway in the National Energy Policy Act of 1992 (P.L. 102-486). Section 1701(b) of the Act states:

> *"… the items which may constitute a "fishway" under section 18 for the safe and timely upstream and downstream passage of fish shall be limited to physical structures, facilities, and devices necessary to maintain all life stages of such fish, and project operations and measures related to such structures, facilities, or devices which are necessary to ensure the effectiveness of such structures, facilities, or devices for such fish."*

Note that Congress used the terms "*safe,*" "*timely,*" and "*effectiveness*" when providing its guidance on fishways. It is for that reason that NMFS fishway prescriptions on Atlantic and Gulf coastal rivers often speak in terms of providing "*safe, timely, and effective*" fish passage. The terms themselves, however, were not specifically defined by Congress. Although it is not NMFS' intention to further define those terms in this document, review of past Atlantic and Gulf coast prescriptions can help individuals better understand the general context in which NMFS has discussed "*safe, timely, and effective*" fish passage in the past at some east coast projects.

Safe passage has been described as facilitating upstream and downstream passage of migrating diadromous fish with minimal injury or mortality resulting from the project barrier or impediment. Ideally, the safe passage objective is 100% survival; however project-specific objectives typically reflect the details of restoration goals, site conditions, and project operation limits. ***Timely passage*** has been described as minimal delay of migration movements past the barrier to the extent needed to achieve restoration goals. Excessive delay of passage can result in adverse effects on reproductive potential through many factors. Site and project operational considerations and target species should be considered in order to promote the best achievable passage. ***Effective passage*** is typically achieved when most if not all diadromous fish arriving at the barrier successfully pass to upstream/downstream habitats without impact on their natural biological functions. Ideally, 100% of the individuals of the target species would be passed; however, as with rates of safe passage, project-specific objectives will reflect the details of restoration goals, site conditions, and project operation limits.

Impacts on Diadromous Fish

The FPA provides decision-making considerations applicable to hydropower projects licensed by the FERC; however those considerations can also be helpful during assessment of potential need for fish passage at other barriers and structures. Important considerations include: 1) whether diadromous fish are adversely impacted by project structures and operations that block or impair fish movements and 2) whether the specific fish passage design will provide for the safe, timely, and effective upstream and downstream passage of fish to mitigate this impact.

Technical Considerations for Effective Fish Passage Design

NMFS has found at past projects along the Atlantic and Gulf coasts that a thorough integration of the following technical considerations is an important first step: presence or absence of target fish species, fish behavior and timing of migration peaks, fish physiology and biomechanics, hydraulic analysis, and mechanical and structural engineering design concepts compatible with the physical characteristics of the barrier or dam. In some cases, installation of fish passage was not viable because of adverse habitat quality above a dam, total absence of former natural spawning runs, or significant threats imposed by harmful exotic and invasive species potentially passed upstream or downstream to adversely affect river ecology. When a barrier or dam is obsolete or abandoned or in dangerous disrepair, breaching or removal of the structure may have been a more important objective than installation of a fish passage system. A collaborative approach for fish passage evaluation that includes resource agencies, Indian Tribes, non-government organizations, local governments, and interested private citizens has been an effective way to develop the needed information.

Chapter 5. Dam Removal or Notching

Application

Complete or partial removal of dams (partial removal is often called notching or breaching) has been shown to be a simple, viable option for fish passage at some dam barriers. Frequently, low head dams that no longer serve their function or present safety or liability hazards are excellent candidates for removal. The cost of full or partial removal of dams may be less than the cost of construction of a fishway or other structure. For example, the Ft. Halifax Project on the Sebasticook River, Maine, was slated for fish passage per the provisions of a settlement agreement. As part of the settlement, fish passage could be attained by a fish lift, breach, or full removal. The final environmental assessment from FERC evaluating the options indicated full removal at $980,000; a fish lift was estimated at $4,000,000 (FERC 2003a).

When implemented correctly, both full dam removal and notching have the added benefit of restoring connectivity of rivers in both upstream and downstream directions for a wide variety of fish and other aquatic species. Full dam removal also eliminates the potential for long-term maintenance and liability associated with structures remaining after notching. However, many considerations for selecting dam removal or notching, or other means for fish passage, are important to consider (even for non-functional dams), including water supply, flood control, presence of contaminants in impoundment sediments, alteration of the hydrography, and impacts to substrates, banks, wetlands and structures above and below the dam.

In developing a plan for dam removal or notching, information pertaining to the operation, structure, and performance of the remaining site has proven critical to the success of the restoration goals. Below is a brief discussion of each element plus some factors that have been used for planning dam removal and notching projects.

Operational Design

Dam removals have been targeted for their overall restoration of river morphology and hydraulics to a pre-dam condition. Historic alterations to the river are often associated with the dam, (e.g., channelization of the river, proximity or inclusion of bridges, buildings, or other structures, flow diversions, flood control, etc.) and have influenced the overall dam removal design. Among other tools, Hydrologic Engineering Centers River Analysis System (HEC-RAS) and/or two- or three-dimensional computational fluid dynamic (CFD) analyses are used to account for natural and anthropogenic features in estimating post-removal velocities and hydraulics. Purpose-designed features – attributes included in the design that address specific needs - may also be incorporated into a dam removal design to mitigate for site characteristics that prevent attainment of either a pre-dam condition or minimum velocities or turbulence. Purpose-design features can include short sections of technical fishways (e.g., through a pre-existing structure or steep ledge), nature-like fishways, or other modification of the dam structure. In the case of dam notching, the operational design typically targets resultant water velocities through a notch below *burst or sprint swimming speeds* of target species at flows representative during peak migratory periods. Ideally, resultant velocities would be no more than maximum sustained swimming speeds of target species, but higher velocities may be acceptable if the distance and duration that target species must swim at burst speeds is short enough for a significant proportion of the population to be able to pass the velocity challenge. For most species, distance/duration data for burst or sprint swimming are unknown; general estimates of swimming speeds (but not durations) are available from Bell (1991); additional data for eastern fish species are described by Haro et al. (2004). Refer to example swimming speeds in Appendix I, Definitions. Typically, notches for dams in excess of 3 feet in height should be carefully considered, to ensure that resultant velocities of an open channel notch do not exceed sprinting or burst speeds of most fish species.

Structural Design

Dam removals have typically followed engineering deconstruction protocols appropriate for the dam structure. Post-removal designs have included measures to ensure the end result is hydraulically and structurally stable to withstand normal variation in river flow, debris, ice accumulation, drought periods, etc., and to maintain function over the long term (including any incorporated purpose-designed features). With fully removed dams, fish can benefit from a zone of passage for fish with significant width and depth (at least 1.5 times the maximum body depth of target species) throughout the migratory season (Haro et al. 2008). Natural features underlying constructed dams (e.g., ledges, bedrock, falls, or rapids) may be retained if they are desired or represent an original partial barrier for fish. In some situations, management agencies may recommend modification of the natural barrier to enhance passage effectiveness. Barriers or other threats to upstream or downstream migrating fish identified post-removal (e.g., alteration of migratory corridors, increased turbidity, etc.) are analyzed and typically addressed as needed through adaptive management plans developed during the design phase.

Notches are typically designed to provide zones of passage while maintaining some aspects of the dam structure. Notches are designed to be a stable, integral part of the dam structure and reinforced if necessary to prevent erosion of the remaining dam structure. Modifications to the notch may be necessary to prevent destabilizing scour or bank erosion associated with the downstream flow jet. Turbulence within the notch should be minimized if possible, but may be acceptable if the notch requires some integral energy-dissipating structures to keep velocities low. Design features which create flow separation, plunging flow, and air entrainment should be avoided or minimized whenever possible. For benthic-oriented or smaller species (e.g., juvenile eels), it is helpful for the notch to incorporate elements that result in a lower velocity boundary layer, as would be found in a natural river bottom. Similarly, the upstream corners of the notch may be designed to facilitate passage along low-velocity boundary layers on the edges of the notch. While smooth corners with large radii will minimize turbulence, they also tend to decrease depth and increase velocity through the notch.

Figure 5-1. Dam removal before and after. *Above:* Steele's Mill Dam, Hitchcock Creek, Pee Dee River, North Carolina.

Figure 5-1. (cont.) Dam removal before and after. *Above:* West Winterport Dam, Marsh Stream, Winterport, Maine.

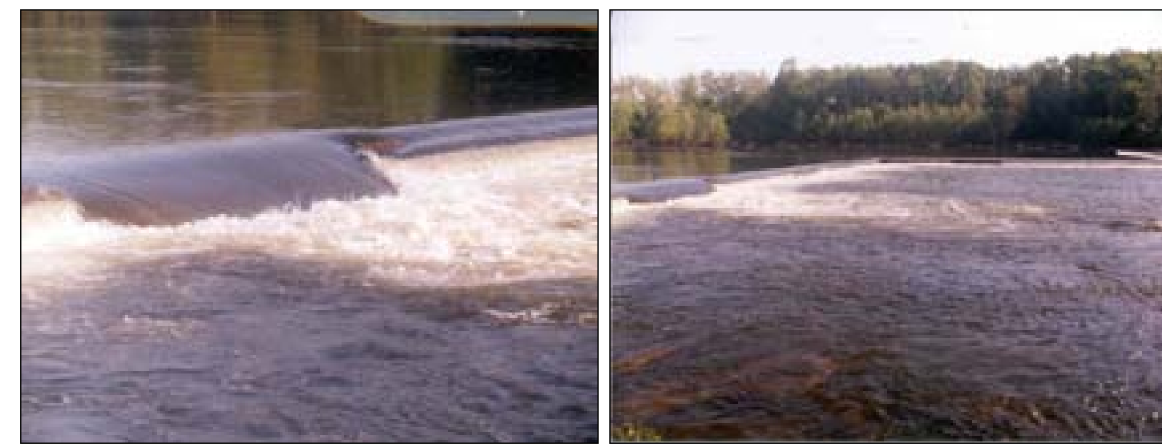
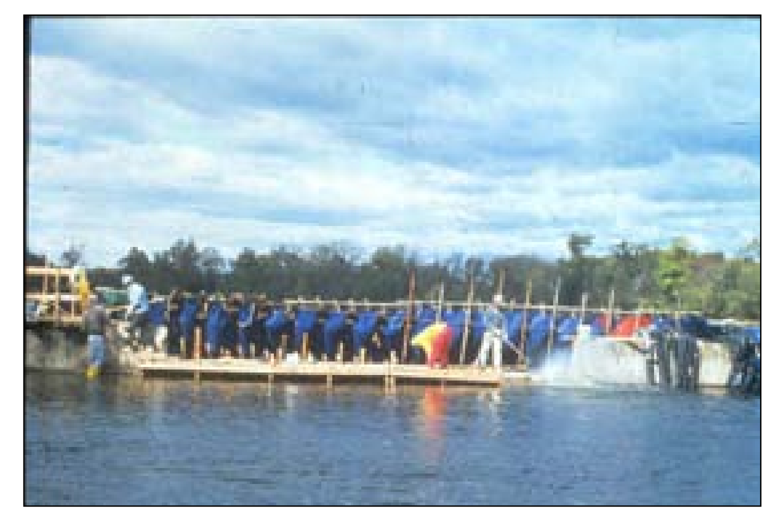


Figure 5-2. Williams Dam Notch, James River, Virginia. *Above:* completed notch; *Below:* Notch under construction. *Dick Quinn, USFWS.*



Performance

The goal for removal of dams (Figure 5-1) or notches (Figure 5-2) has often been to replicate or approach pre-dam hydraulics and fish passage conditions. Often the level of pre-dam fish passage is unknown, and in the absence of historical data, removed or notched dams should be passable to most target species with a minimum of delay.

Design Criteria

Design criteria for dam removals and notches are dependent on site characteristics, dam height, river size and flow, and swimming capabilities of target fish species. Below is a list of design criteria used in some past planning dam removals and notching projects.

For dam removals:

- Restoration of original stream gradient or adjacent gradient conditions.
- Ability of target fish to pass through dam removal zone during migration.
- Minimization of turbulence, plunging flow, air entrainment, reverse flow, and eddies within the dam removal zone.

For notches:

- Consider for dams less than 3 feet in height and for which a full dam removal is not feasible; higher dams may be considered although other issues may affect success of fish passage.
- Site the notch at the natural point where fish concentrate.
- Maximum through-notch velocity equal to or below maximum sustained swimming speed of target species; higher velocities may be considered if sprint swimming speeds and durations of target species and path distance of velocity field are known.
- Notch width and depth should be as large as practicable, otherwise recommend minimum notch depth of 1.5 times body depth of target species, minimum notch width of 10 times body width of target species, or 50 times body width for schooling species (Haro et al. 2008).
- Overall design should minimize turbulence and air entrainment through the notch.
- For benthic-oriented or smaller species (e.g., juvenile eels), it is helpful for the notch to incorporate elements that result in a lower velocity boundary layer, as would be found in a natural river bottom.

Design Review

Fish passage may be needed for a variety of land and water resource development, transportation, or environmental restoration projects. The requirement to implement passage is often determined during regulatory actions, (e.g., licensing of hydroelectric projects by the FERC) or stakeholder interests (in a restoration effort). Once the decision for implementing fish passage has been made, a final design may take many steps to develop, including site studies and various levels of designs. During the FERC hydropower licensing process, fish passage design is typically developed during the FPA consultation (this consultation under the FPA is different from a consultation required under the ESA). The consultation process is accomplished through coordination with the NMFS, USFWS, and state fishery resource agencies. The design has often been based on the best available information about physical site characteristics and biological considerations of the target species. Early coordination with NMFS and USFWS fish passage biologists and fishway engineers has often facilitated development of a preliminary design, planning, and regulatory approval. The fish passage (fishway) design process for upstream and downstream migrating fish provides an opportunity to develop safe, timely, and effective fish passage facilities appropriate for the specific site and target species. Identifying the most appropriate and cost effective fishway design to achieve this goal will aid in meeting fishery management objectives, including minimizing injury, stress, and migration delays; restoration; and sustainable diadromous fish populations in the future.

Site Information for Fishway Design

Understanding the site topography, channel morphology, river hydrology, and characteristics of the dam or barrier has been valuable in planning and designing fishways. The following list identifies sources for gathering information at hydropower and non-hydropower facilities.

1. River basin map showing the project location in the watershed and the location of other nearby barriers or dams and existing or proposed fish passage facilities.
2. A site plan and construction drawings showing existing and proposed project features and the proposed layout of the fishway, including turbine types, size and rated capacities, minimum and maximum operating flow, and headpond range, as well as description and dimensions of the project barrier or dam, spillway design, gate types, and capacities; photos of the site and facilities also are helpful.
3. Topographic surveys upstream and downstream of the project and at the proposed locations of fishway entrances and exits. Headwater and tailwater rating curves that show the relation between water level (stage) and flow volume (discharge) above and below the barrier. Note that for some barriers at the head of tide, tailwater elevations will be influenced by both streamflow and tidal fluctuations. An example of headwater and tailwater rating curves is shown in Figure 6-1. If hydraulic modeling such as *HEC-RAS* is used to develop rating curves, the model should be calibrated using multiple stage-discharge measurements from field surveys.
4. River or stream flow data from an appropriate USGS gauging station, if available, including daily and monthly flow data, flow duration exceedance curves based on the historical flow record, and river basin drainage area upstream from the barrier or dam. If gage data are unavailable or only available for a short period of time, appropriate estimation methods for generating a useful flow record should be included along with description of data sources and methods.
5. A description of project flood control, navigation lock, diversion flows, and hydropower operations that may influence fish migrations and movements at the proposed fishway location (load following, peaking, powerhouse flow capacity, minimum and maximum operational flows, operational period, special operations such as flash board replacement, etc.).

6. Upstream and downstream river morphology in the vicinity of the project, including a discussion of channel stability, degradation, and sand/sediment movements that could influence fishway performance characteristics.
7. A description of nuisance aquatic vegetation, ice, or debris accumulation problems that may influence fishway design or performance.
8. Site access for construction equipment, operations, maintenance, and biological study, trapping, trucking, etc.
9. Other information based on site specific biological assessments.

Biological Information for Design

Understanding the biological needs of target species will influence the parameters of the fishway, including the type of fishway, siting, and operation. The following list identifies types of information useful for the design of a fishway.

1. Target fish species, spawning or migratory run size (design population), migration periods, spawning location, and estimated timing of each life stage arriving at the barrier and fishway during upstream and downstream migration.
2. Estimated periods of upstream and downstream migration and estimated numbers of other migrant fish that may influence fishway performance and capacity.
3. Predator species expected to be present, including fish, reptiles, birds, and mammals.
4. Design passage flows for upstream and downstream passage for each target species across life stages during both high flow and low flow conditions.
5. Fishery management plans or comprehensive water resource plans.
6. Proposed security plans and facility features to guard against unauthorized human activity, poaching, vandalism, etc.
7. Special fish passage management or monitoring objectives related to operation of the fishway (e.g. counting, trapping, or exclusion of certain species).

Design Development and Review Process

The fish passage design process may be tiered into steps or phases as described below. Including NMFS, USFWS, and state resource agency staff in each phase of the process facilitates development of the final design.

Preliminary site survey: – The initial investigation of the site or alternative sites to evaluate their suitability for the fishway includes considering potential problems and limitations.

Identification/evaluation of conceptual design alternatives: –Identify various fishway designs that may meet fish passage objectives at the project site. The evaluation may provide an initial list of alternative conceptual designs for a detailed feasibility study.

Feasibility study: – This phase is an "evaluation of conceptual design alternatives," which includes a more detailed examination of site characteristics, conceptual design details and limitations, and estimated costs for each design. The feasibility study supports selection of the preferred alternative design.

Preliminary design: – Includes more detailed site investigations, geotechnical evaluations, preliminary drawings, fishway dimensions and required flows, and more accurate cost estimates. Completion of the preliminary design phase document should be suitable for budget planning and higher-level approvals, and for review and comment by review agencies involved in the project planning process. This phase may be considered the 30% completion design phase.

Modeling: – At this stage it should be determined whether modeling is needed to answer questions concerning the flow regime in and around the entrances and exits of the upstream and downstream fishways. The modeling may be done with a physical model or with a CFD model.

Detailed design phase: – This phase builds on the preliminary design and incorporates review comments, recommendations, and the results of modeling. This phase generally includes the 60% and 90% designs, including production of a full set of electronic drawings and 11-by-17 inch paper drawings for each agency to review and comment. The end product of this phase is the final or functional design and specifications in preparation for the bid process.

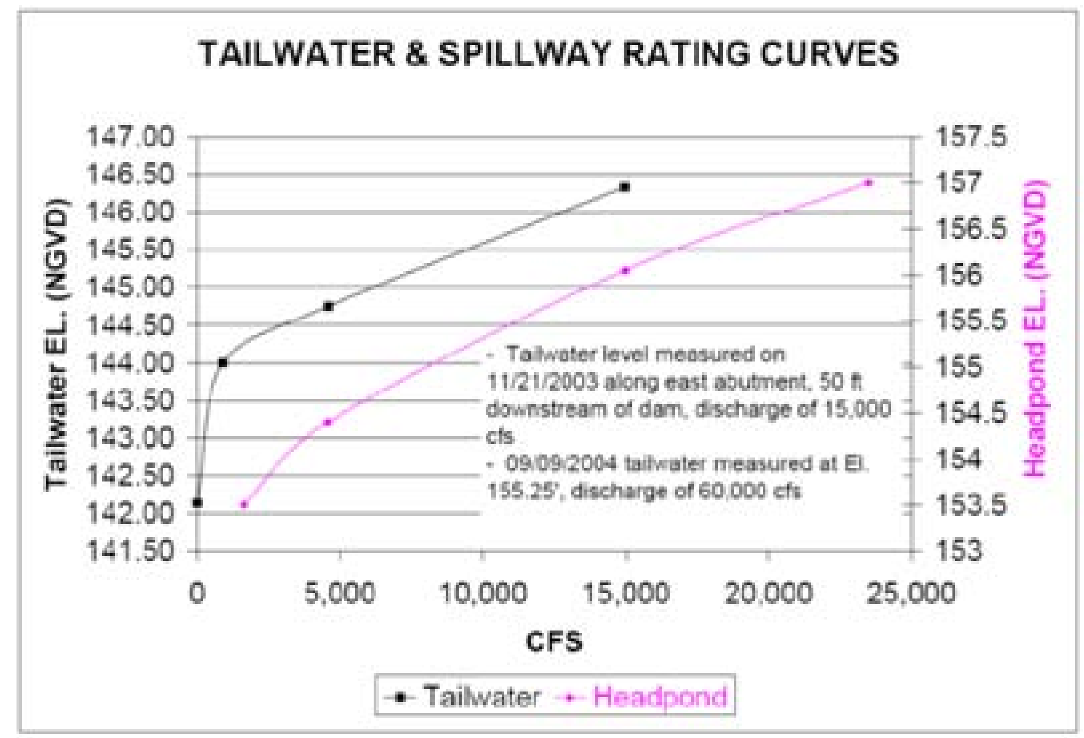


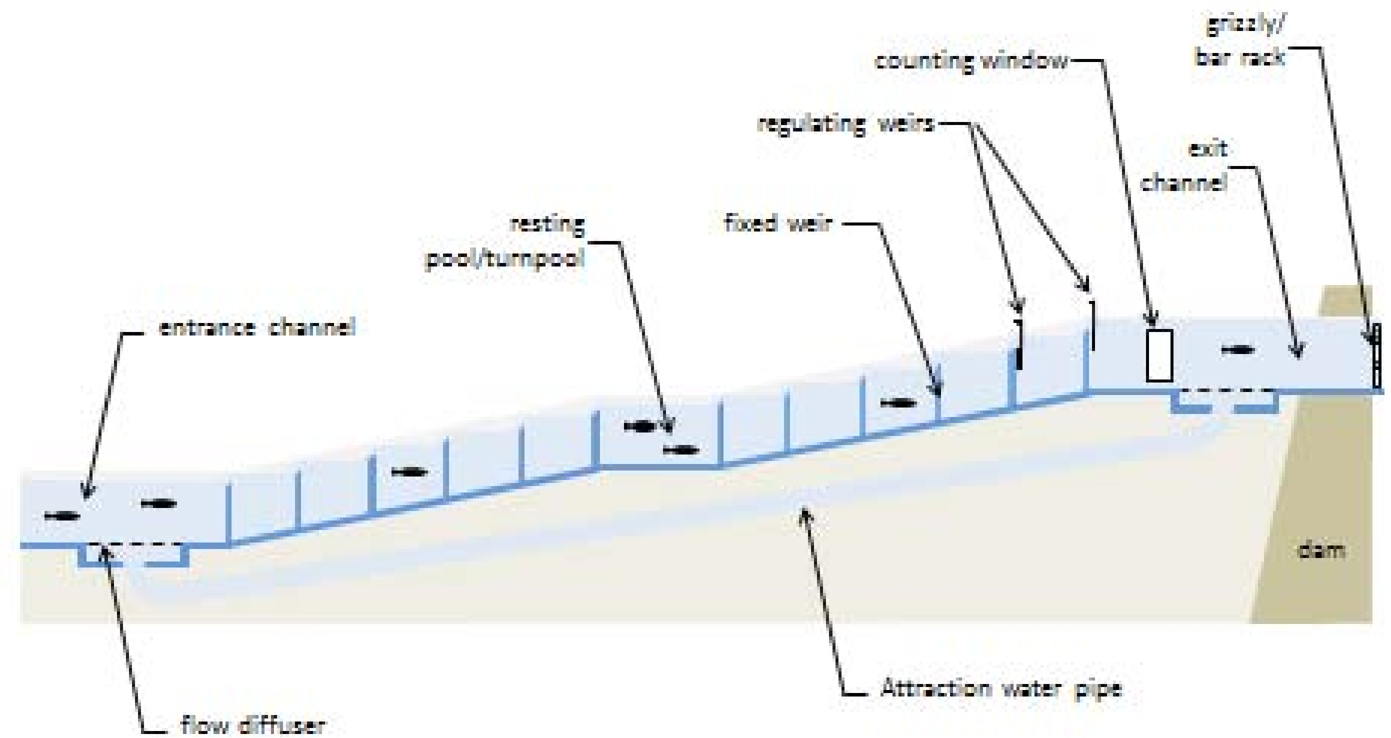
Figure 6-1. Headpond and tailwater rating curves. Example from the Columbia Diversion Dam, Broad River, South Carolina. *Kleinschmidt Associates* 2006.

Introduction

NMFS' goal for upstream passage systems has been to provide safe, timely, and effective upstream passage for migratory anadromous fish species at an artificial impediment or barrier. This requires careful integration of fish behavior, physiology, and biomechanics with hydraulic analysis, hydrologic study, and bioengineering (NMFS 2008b). Upstream fish passage systems include fishways designed for volitional passage and other non-volitional passage facilities, such as fish lifts and trap and transport systems. Figure 7-1 shows an aerial view of the Columbia Fishway, a vertical slot design at the Columbia Canal Diversion Dam on the Broad River, South Carolina, which was designed with the aforementioned integrated hydraulic and biological features in mind. Most of the design specifications and criteria mentioned in this chapter are referenced in the *U.S. Fish and Wildlife Service Fish Passageways and Bypass Facilities Training Course Manual* (USFWS 2000).

Three basic components of an upstream fishway generally included among various fishway types are the *fishway entrance* below or at the foot of a barrier, the *body of the fishway* to convey fish, and the *fishway exit* that safely releases fish upstream from the barrier (Figure 7-2). Characteristics of the impediment or barrier vary with height, configuration, water flow, and many other physical factors and have bearing on design of the fishway sections between the entrance and the exit. Following are descriptions of typical upstream fishway components and design flow considerations.

Figure 7-1. Aerial view of the Columbia Diversion Dam and Fishway on the Broad River, Santee River Basin, South Carolina. The dam was constructed in 1824, and the vertical slot-type fishway (upper right) was completed in 2007.



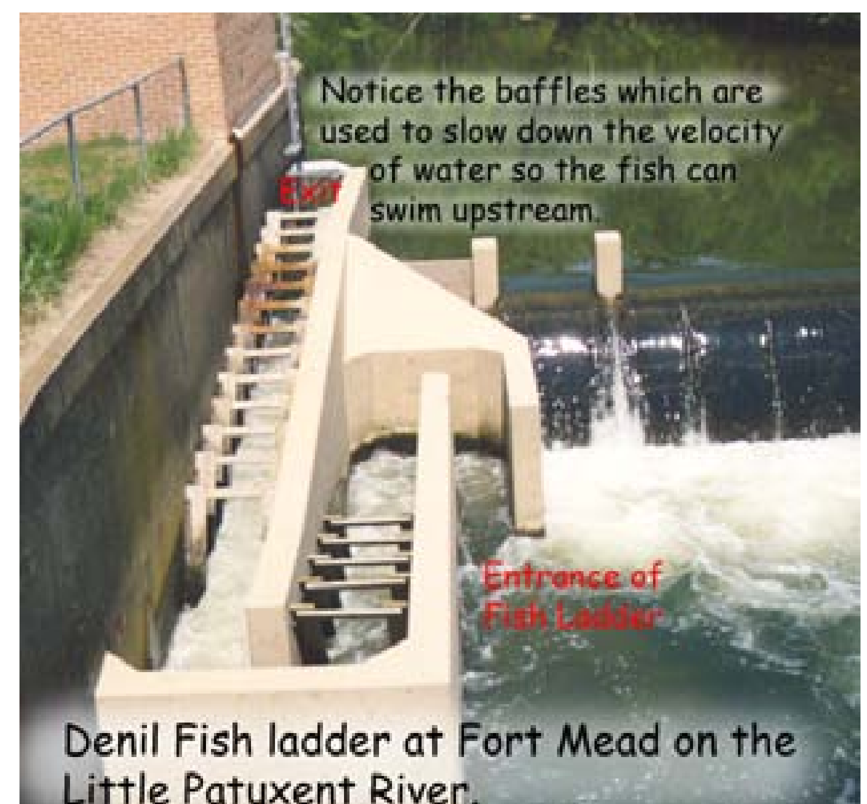


Figure 7-2. Typical upstream fishway or fish ladder diagram. *A. Haro, USGS*
Left: Example Denil-type fishway showing basic components. Fort Mead Dam, Little Patuxent River, Virginia. *USFWS*

Fish Passage Design Flows

Spawning migrations of Atlantic coast anadromous fish correlate with seasonal increased river flow conditions and water temperatures during late winter and spring months (McDonald 1887). At times, seasonal high flows and significant fluctuations in water temperature may retard anadromous fish upstream movements until moderate flow and temperature conditions return. Exceptional drought or low flow conditions may also reduce or delay the extent of upstream migrations for some species, restrict of *zone of passage* flows, and result in the emergence of barriers. The design river flow range for fish passage at a specific barrier describes the upper and lower bounds of river flows to ensure adequate passage for all target species over their migration period. During development of fish passage facility designs, site-specific information is critical for determining the design time frame and river flow conditions.

Low Flow Range: A general recommendation often used for the design low flow range is the mean daily average river flow that is exceeded 95% of the time during the spawning migration period for target species normally present in the river basin and at the fish passage site. This criterion was originally developed in the Pacific Northwest for passage of salmonid species (NMFS 2008b). The fish passage design low flow is the lowest stream flow for which migrants are expected to be present, migrating, and dependent on the proposed facility for safe passage. For passage of Atlantic anadromous species, this criterion is considered a helpful general guideline for fish passage design along with consideration of target species, individual barrier site conditions, and operational characteristics.
A useful technique for determining the design low flow range can include analysis of available mean daily flows recorded by stream gages during the previous 25 years or best available data during the fish migration season. The U.S. Geological Survey generally has maintained stream gages in most Atlantic coast river basins since the 1930s or longer. If adequate flow records are unavailable or of shorter duration, well-supported estimates have been used.

High Flow Range: The general recommendation for design high flow range is the mean daily average river flow exceeded 5% of the time during periods when migrating target species are normally present in the river at the fish passage site. The fish passage design high flow is the highest stream flow for which migrants are expected to be present, migrating, and dependent on the proposed facility for safe passage. Consistent with the approach for determining the low flow range, the mean daily flows during the fish migration season for the previous 25 years may be used to determine the high flow range. If adequate flow records are unavailable, well-supported estimates have been used. The fishway design should provide for protective shutdown of the facility during higher flood flow events, if needed, with a quick return to full operation when the river drops to within the design flow range.

Swimming Speed Considerations in Fishway Design

Anadromous fishes ascending rivers to reach spawning habitats exhibit *swimming speeds* characteristic of each species. Fishway bioengineering experts categorize swimming speeds as *cruising* speed, *sustained* speed, and *burst* speed. Burst speed is sometimes referred to as *sprin*t speed, or *darting* speed. Through fish behavioral studies, those speed categories can be defined for each species. An example reference to behavioral swimming speed studies is the *Fisheries Handbook of Engineering Requirements and Biological Criteria* by Milo C. Bell (1991). Bell's swimming speed studies addressed a number of target species, including American shad, river herring, and striped bass. Swimming speed studies are in progress on Atlantic and Gulf coast river basins, and new, more specific data will continue to be available in the future. Data describing swimming speeds assist in development of hydraulic and structural design criteria for successful fish passage, and for fish entrainment protection screening and bypass facilities for downstream passage. Bell (1991) includes swimming speed data as described below.

Cruising speed: Cruising speed refers to the normal "over the ground" swimming speed utilized by a fish species during upstream migration through natural river and stream channel conditions. The cruising speed is normal "through the water" migration speed minus water velocity, yielding the over the ground cruising speed. For example, Bell (1991) suggested American shad 12 to 14 inches long exhibited a cruising speed of 2 to 4 feet per second.

Sustained Speed: This speed is defined as the increased speed maintained by a fish during a channel riffle, run, or a series of fishway pools. For example, for an American shad 12 to 14 inches long, sustained speed is 4 to 7 feet per second.

Burst Speed or Darting Speed: Burst speed is defined as the maximum speed capability demonstrated by fish during a short upstream movement challenge, such as escape from a predator, or a short high velocity current. As an example, the burst speed of American shad has been reported as 7 to 15 feet per second.

Example swimming speed data from by Bell (1991) are presented in Table I on the following page. Additional behavioral studies are now being undertaken for a variety of fish species to improve passage efficiency and effectiveness.

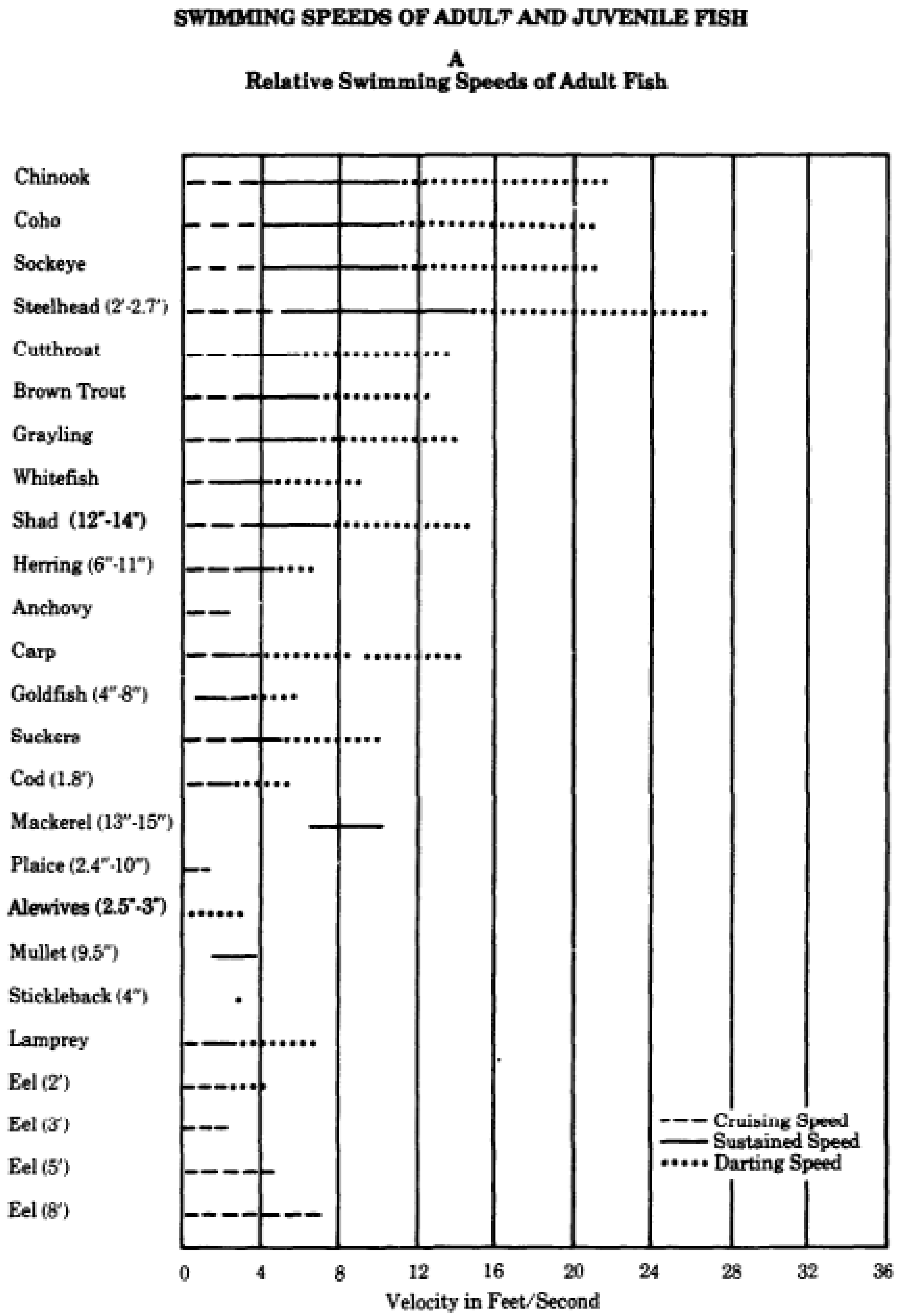


Table 1. Preliminary swimming speed data from Bell (1991).

Fishway Entrance

The fishway entrance is designed to attract upstream migrant fish to the fish passage facility as they encounter a barrier or dam. The fishway entrance is likely the most critical aspect to the facility design (NMFS 2008b). Siting, design, and effective attraction flow are important features of the fishway entrance, and the overall ability of the fishway to effectively move fish past the barrier without delay. The fishway entrance may be a gate or slot structure, or a constructed nature-like design channel entrance with an effective fishway attraction flow. NMFS experience at fishways indicates the following elements of the fishway entrance are critical: 1) location/orientation, 2) flow characteristics in relation to existing channel features below the barrier at high, medium, and low river flows, and 3) synchronization with hydropower operations at an active hydropower project. General references for this chapter include NMFS (2008b) and USFWS (2000). An example of a fishway entrance at the Columbia fishway, on the Broad River, South Carolina, is shown in Figure 7-3.

Figure 7-3. Example entrance for a vertical slot fishway. The Columbia Diversion Dam on the Broad River, Santee River Basin, South Carolina. Note the staff gauge (on the wall at the right) installed to allow monitoring of entrance hydraulic head differential above/below the entrance gate.

Location at the Barrier: The fishway entrance is generally located at the most upstream point of fish migration, typically at the base of a dam, or where flow patterns cause fish to collect. The optimal entrance location varies with flow conditions, and sometimes multiple entrances are required to account for different conditions. Having a variety of fish species with differing preferences complicates siting and/or selection of fishway type. Study of flows, including 3-dimensional CFD modeling and physical models, and observation of fish movements and areas of concentration in relation to the configuration of the barrier have informed selection of the entrance location. At active hydropower projects, operational characteristics, existing tailwater channel morphology, barrier effects on flow, areas of high water velocity and turbulence, and calm water areas may influence the optimal location of the entrance. It is important that the entrance be located where fish are most likely to find and be attracted to the fishway attraction flow (NMFS 2008b). Alteration of channel morphology has been incorporated into project designs to provide high and low flow access channels and holding areas or pools adjacent to the fishway entrance(s). An example project with altered channel morphology for high and low flow access channels is the Columbia vertical slot fishway (Figure 7-1 and Figure 7-3).

Entrance Orientation: Low flow entrances generally are oriented 45 to 90 degrees to the tailwater flow, and high flow entrances generally are oriented from 45 degrees to parallel with the flow (B. Rizzo, personal communication). Site specific conditions such as spillway location and overflow depths may require variations from those criteria. Physical or CFD modeling can be useful for optimizing entrance location and orientation.

Operation considerations: Entrance gates are designed to provide effective entrance characteristics at the full range of design flows and hydropower operations. Adjustable *weir* gates that can rise and fall in synchronization with tailwater elevations maintain optimal *entrance head* if tailwater elevation fluctuations are significant. When tailwater fluctuations are limited during the fish migration season, adjustable entrance gates may not be required. *Auxiliary water systems* are also employed in combination with entrance gates or *stop logs* to achieve optimal entrance flow characteristics. Entrance gates may have adjustable weirs, vertical slots, or stop logs. Bottom opening gates (e.g., sluice gates) that require fish to swim through orifices with structures above the channel have been avoided at most sites.

Dimensions: Depth and width at the fishway entrance depends on size and flow conditions of the river or stream, attraction flow requirements, barrier dimensions, and biology of the target species. As an example, a minimum entrance width of 4 feet and depth of 6 feet is often used for upstream passage for American shad (Quinn 1994).

Attraction Flow

Attraction flow is important to achieve the best available upstream passage (NMFS 2008b). Without adequate attraction flow, upstream migrant fish will not be drawn to the fishway and instead may be attracted to hydropower turbine flows or broad spillways that overwhelm or "dwarf" the attracting ability of fishway entrance flows. As an example, a general guideline and objective for attraction flow in the Pacific Northwest is 5% to 10% of the fish passage design high flow for rivers with mean annual flows exceeding 1000 cfs (NMFS 2008b). For Atlantic coast river basins, USFWS typically recommends 3% to 5% of the hydropower turbine flow as a for attraction flow at hydropower dams for shad and herring (B. Rizzo, personal communication). At sites with competing spill flows during the migration season, using a percent of the design river flow may be more appropriate for establishing an appropriate attraction flow. Individual site and project conditions, target species migration periods, and operational flexibility are considered in establishing the best design attraction flow capacity achievable within project constraints. Two auxiliary features used to enhance the monitoring and functionality of attraction flow—staff gauges and entrance pools—are described here.

Staff Gauges: Easily readable staff gauges at the entrance pool and in the tailwater immediately outside the fishway entrance allow observation of the entrance head drop.

Entrance Pools: The entrance pool delivers the attraction flow, combining flow from upper sections of the fishway with auxiliary water system flow delivered through floor or wall *diffuser* gratings. The entrance pool provides critical attraction and guidance to fish on their way to the first fishway weir, vertical slot, or baffle.

Auxiliary Water Systems

Auxiliary Water Systems (AWS) are a design component at most larger fishways to provide an additional source of attraction flow for adjustment of fishway hydraulic conditions to optimize passage (Figure 7-4). Water flows routed directly through a fishway from the project *forebay* or *headpond* in some circumstances may not provide adequate attraction flow at the fishway entrance. AWS have also been used to augment flow at other locations within a fishway, including the entrance channel (above the entrance gate), trap pool flows, transport channel flows, exit control sections, or counting station pools. The AWS provides additional flow routed by gravity from the forebay or by pumps from the tailwater below the dam. Components of a typical AWS include a separate intake with trash rack, fish screens, a flow control gate, piping to deliver flow to the needed section of the fishway, an energy dissipation zone with an arrangement of baffles, and/or diffuser screens usually located in the floor of the fishway. Various engineering design criteria are used to maximize the performance of the AWS attraction flow augmentation system, and those criteria are beyond the scope of this overview document.

In the past, obtaining adequate attraction flow for fishways was a challenge at hydroelectric projects because the needed flows were thought to jeopardize the economic viability of hydropower operations. In recent years, small power-generating turbines (attraction flow turbines) have been used or proposed in the AWS to help offset the cost of augmenting fish attraction flow at the fishway. An example of the small turbine runner design is shown in Figure 7-5. Intakes for attraction flow turbines should be adequately screened to prevent entrainment or impingement of fish by the AWS.

Transport Channels

A *transport channel* conveys water flow between components of an upstream fishway, and is designed to provide attractive conditions for fish passage while minimizing stress or delay (Figure 7-6). Dimensions, velocity ranges, and lighting conditions are the principal design considerations for transport channels. In particular, the ability to provide ambient natural lighting without sharp light intensity transitions has been found to be an important aspect for avoiding stress or delay (Larinier and Travade 2002). In some cases, artificial lighting systems have been used for fishways to avoid harmful light transitions and to promote movements by fish.

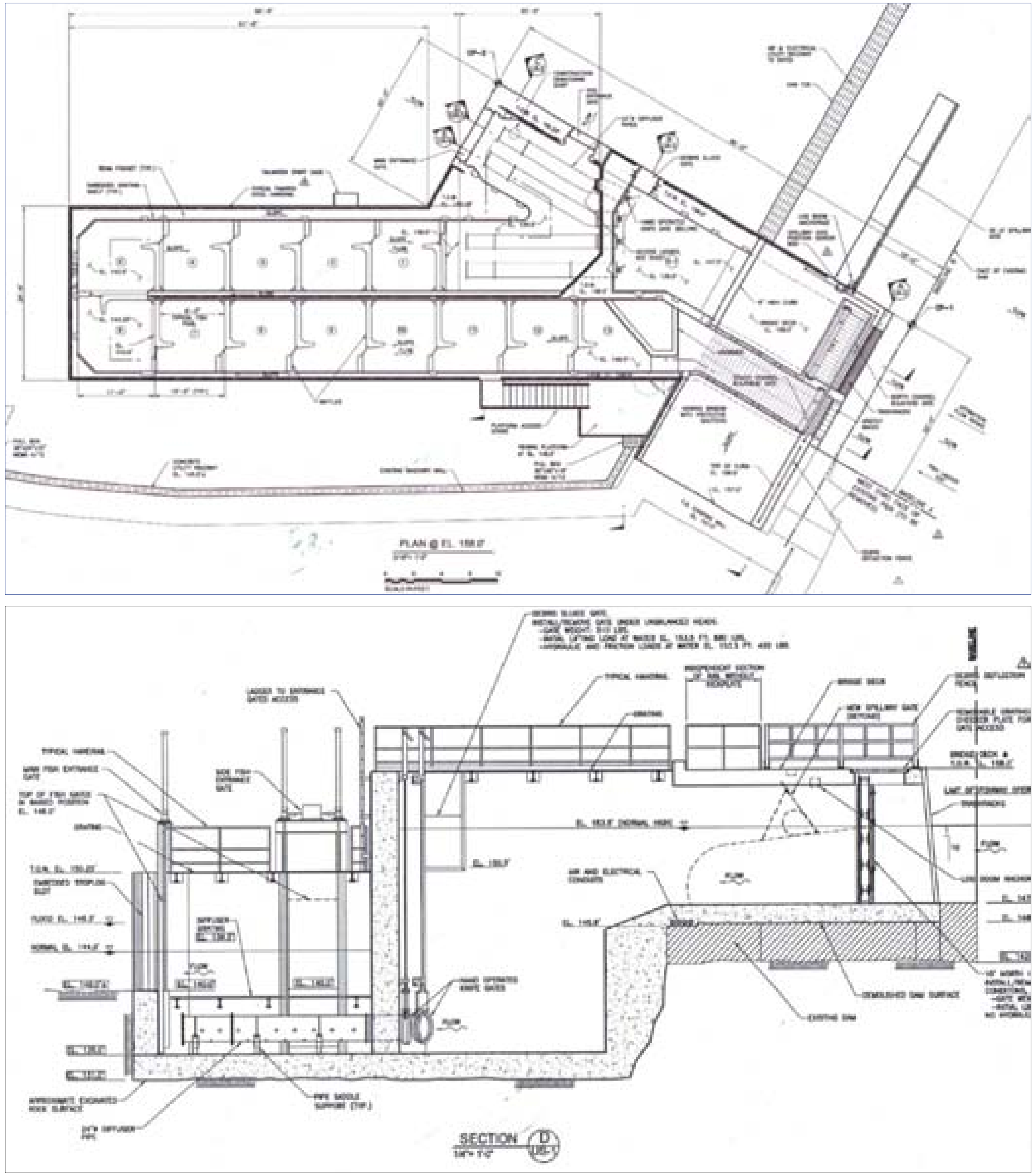


Figure 7-4. Auxiliary attraction water system at Columbia Vertical Slot Fishway, Santee River Basin, South Carolina. *Upper*: Plan view shows AWS intake adjacent to fishway exit channel. *Lower*: Section view shows intake, flow gallery, and attraction water valve and diffuser below the fishway entrance pool. *Kleinschmidt Associates*

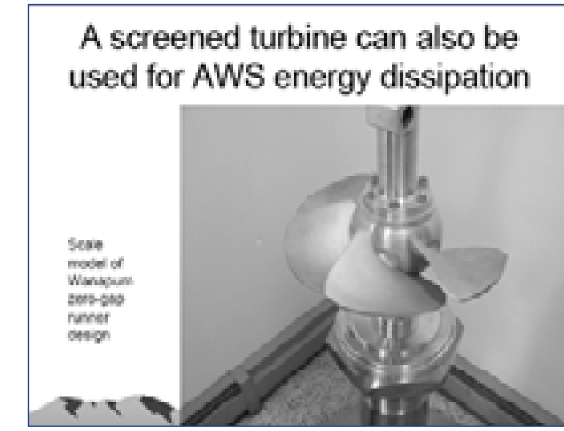


Figure 7-5. Example auxiliary water system turbine. *NMFS 2008b*

Figure 7-6. Example Denil fishway transport channel. Potter Hill Dam Pawcatuck River, Westerly, Rhode Island. *Below:* Transport channel between the entrance and the fish lock, St. Stephen Fish Lock, Santee River, South Carolina.

Fish Counting Stations

Upstream passage *counting stations* are typically located in the upper section of the transport channel or in the fishway exit, and provide an effective means of counting fish prior to exiting the fishway on their way upstream. Counting stations are a valuable tool for fishery managers and assist in assessment of spawning run size, fish health, relative abundance, and in support of research projects. Counting stations typically include a visual observation and counting window, a *crowder* structure with *picket leads* or screens to move fish closer to the counting window for observation, and a *viewing room* sized for visitors and/or fish count technicians. Counting technicians use a variety of tools for counting fish, including hand counting devices, electronic fish counters, video cameras for visual counts or for use with recognition software, adult passive integrated transponder (PIT) tag detectors, and radio or hydro-acoustic counting devices. Counting stations are designed to prevent any interference with fish movements (from, for example, light or flow transitions) or normal operation of the fishway. Example counting stations and viewing windows at the Holyoke and Columbia Fishways are shown in Figure 7-7. Some features of a counting station design are considered below.

Figure 7-7. Fish counting station examples. *Left:* station window at Holyoke Fishway, Connecticut River, Holyoke, Massachusetts. *Right:* station window at the Columbia Fishway, Broad River, Columbia, South Carolina.

Location: Upstream counting stations are generally located in areas that have a stable flow of relatively low velocity (1.5 feet per second) at an accessible location typically near the fishway exit.

Transport Channel Configuration: The pool or transport channel zones below and above the counting station are designed directly in line to avoid interference with fish movements or delays.

Counting Window Slot Width: In most cases, the fish counting "slot" area has a minimum width of 18 inches between the window surface and the viewing backboard surface opposite the window. Most counting windows also include an adjustable crowder to encourage fish movement closer to the window during varying turbidity conditions. The counting window slot width can be increased in consideration of water clarity and when counting is not taking place to maximize fish movements.

Counting Window Orientation: The counting window(s) are vertically oriented and placed to facilitate frequent cleaning access. A free water surface is provided over a counting window and the exit channel. Some migrating fish, including American shad, tend to avoid upstream movement if structures are located above the fishway components (e.g., entrance, transport channel, counting window area, or exit channel).

Window Material: Selection of abrasion-resistant window material allows for frequent cleaning without scratching or damage to the window surface.

Lighting: Natural or artificial lighting is necessary to provide for satisfactory fish identification. Lighting should be indirect and carefully designed to avoid abrupt lighting transitions that interfere with migration behavior.

Transition Ramps: Ramps are used when needed to avoid flow transitions due to head loss through the counting window zone, which can cause fish *fallback*. The purpose of transition ramps is to provide gradual transitions at fishway walls and floors approaching the counting window slot. Transitions should be designed to be more gradual than 1:8 for horizontal or vertical ramps (NMFS 2008b).

Fishway Exit

The *fishway exit* is designed to allow for timely and safe movement of fish to open water above the passage barrier and to allow them to continue upstream migration. The fishway exit design typically includes gates or stop log slots to allow for closure of the fishway for cleaning and maintenance, and trash racks to prevent debris from entering the fishway without interfering with upstream fish movements. Pool and weir designs for larger rivers may require flow control gates, auxiliary water valves, and diffusers for maintenance of stable hydraulic conditions in the fishway pools when headpond elevation fluctuations occur. Exit design details vary with differing fishway types. The fishway exit at Columbia Fishway, on the Broad River, South Carolina, is shown in Figure 7-8.

Location: Location of the fishway exit should include consideration of upstream channel configuration, flow patterns, proximity of shorelines, and location of powerhouse intakes. As fish exit the fishway to the headpond above the barrier, delays in upstream migration may occur due to confusing flow patterns. Fish fallback may result from hydropower forebay flow patterns with circular currents or eddies that lead them near turbine penstocks or spillways. Study of headpond flow patterns can inform the decision process for locating the fishway exit to make it easier for fish to orient to stable flow vectors leading upstream. When feasible, the fishway exit should be located along a shoreline and in an area as far as possible upstream from spillways or powerhouse penstocks to reduce risk of fish *fallback*.

Hydraulic Drop: Exit channel sections generally have a hydraulic drop to support an exit attraction flow to encourage fish movements into the headpond above the barrier. The hydraulic drop specification depends upon site conditions and the behavior of the target fish species.

Public Access: Vandalism has been an issue at some fishway sites. The fishway exit should be protected from uncontrolled public access to avoid damage to the fishway and disturbance of fish.

Trash Rack Bar Spacing: Fishway exit trash racks (often called "grizzly racks") are designed with size and behavioral characteristics of all target species in mind. For example, American shad and other alosines generally require a minimum vertical bar clear spacing of 8 inches (NMFS 2008b). Other larger adult species including shortnose and Atlantic sturgeon and striped bass may require greater spacing to accommodate their large body size. The spacing needed is generally developed during the engineering design planning process in consideration of target species and site characteristics.

Trash Rack Orientation: The fishway exit trash rack is generally sloped back slightly to facilitate manual cleaning on a regular basis. A sturdy railing should be provided for cleaning, and lighting should be provided for night cleaning when necessary.

Trash Boom: Proper installation of a floating trash boom to carry debris to the spillway or a trash sluice on the dam can help reduce debris accumulation on the fishway trash rack.

Automated Debris Removal System: For larger fishways when debris accumulation is expected to be high and frequent, automated systems have been included in the fishway design. If the extent of debris accumulation is unknown during the design phase, considerations for an automated debris removal system can be included in the exit design for later retrofit if needed.

Figure 7-8. Fishway exit at Columbia Vertical Slot Fishway, Broad River, South Carolina. Note the vertical bar "grizzly rack" with bar "clear" spacing of 11 inches and sloping slightly backward to facilitate manual cleaning.

Additional Fishway Design Considerations

Fishways are complex engineering structures with many components and/or moving parts. Not all design considerations are strictly engineering. Safety, lighting, operations, and predation are factors that affect the function of a fishway. Some additional features of the overall fishway design are considered below.

Safety and Security: Considerations for public safety in accordance with state, federal, and local government requirements are typically included in the design. Protection of the fishway may include measures to discourage unauthorized access and vandalism.

Lighting: Natural lighting without sharp transitions should be provided throughout the fishway sections. When natural lighting is not possible, artificial lighting is typically installed. Artificial lighting within the natural spectral range should be provided and designed to operate dependably under all environmental and weather conditions

Protection from Predation: Fishway designs may incorporate features to prevent predation by birds and other species. Typical features may include screening, aerial wires, and automatic water spray devices to keep birds away from the downstream passage exit.

Operation and Maintenance Access: Personnel access for maintenance, repair, and fishway monitoring should be provided in all sections of the fishway.

Fishway Component Edges and Surface Finish: For engineered structures, all metal, wood, and concrete edges and surfaces within the path of fish movements should be smooth and rounded to minimize scale loss and injuries.

Obstructions and Protrusions: Moveable equipment components and protrusions, including valve stems, fastenings, flanges, gate operation cables, and hydraulic ram stems, can interfere with fish passage and should not extend into or obstruct areas within the path of fish movements.

Water Quality: Besides adverse hydraulic conditions, fish may avoid fishways simply because the water is in some way different from the natural river channel (e.g., temperature, dissolved oxygen, etc.). This can be an issue with deeper reservoirs where stratification occurs and the top strata (epilimnion) has different water quality than the reservoir bottom (hypolimnion). While fish passage facilities typically draw their water supply from the surface of a reservoir, turbines draw their water from lower strata in the reservoir. Water at the bottom of some reservoirs may be colder and/or have less oxygen than water at the surface. Thus the quality of the discharges from turbines and fishways can be of different water quality. These differences can result in fish not locating or using an otherwise acceptable fish passage facility. Fish passage designs should take into account the water quality at the project location and source of water for attraction flow.

Introduction

Technical upstream fishways employ engineering designs that are typically concrete or aluminum and provide a cascading effect that slows the water velocity in a measured way to accommodate the swimming speed of target species. These upstream fishways are usually operated to provide continuous *volitional passage* routes for upstream migrant fish at river channel barriers and dams. Volitional passage routes are created through zones of hydraulic and channel flow conditions that allow fish to enter and pass through the fish ladder without injury, undue expenditure of energy, human handling, or excessive delay. Operation of volitional passage facilities can be continuous and year-round. Fish ladders generally fall into one of two categories: baffled chutes and pool and weir. General references for this chapter include: Bates 2000; Clay 1995; Kamula 2001; Katopodis 1992; NMFS 2008b; Quinn 1994; and USFWS 2000.

Baffled Chute Fishways

The purpose and basic design concept for baffled fishways is to reduce the total project hydraulic head to passable increments using a series of baffles, each increment comprising a carefully controlled hydraulic step over a short distance. Baffles dissipate head energy to provide hydraulic conditions suitable for upstream fish movements. This may include resting pools for longer fishways. The Denil and the steeppass designs are two principal variations of baffled chutes in general use (Figures 8-1 and 8-2).

Denil Fishways: *Denil fishways* (Figure 8-1) are the most common baffled chutes fishway because the single-plane baffle of a Denil fishway is easier to fabricate than the multi-plane baffles of the steeppass fishway. Because standard Denil fishways are less effective at energy dissipation than steeppasses, Denil fishways are somewhat longer for similar ease of passage. Within Denil fishways, the highest velocities are toward the top of the water column. Denil fishways are fabricated from many types of materials—metal, concrete, wood, etc. Denil fishways are relatively low cost in comparison with the larger pool-type technical fishways, and Denil fishways in appropriate locations can be generally reliable for passage of adult salmonids and in some cases American shad, river herring, other alosines, and other migratory and resident species (Quinn 1994).

***Steeppasses*:** Also known as the Alaska *steeppass*, these are similar but more complex than the Denil design with higher energy dissipation (compared to the standard Denil design) that permits somewhat steeper angles, or slower water velocities, or shorter ladders (Figure 8-2). Steeppasses are usually fabricated from aluminum in modular sections to allow portability. The prefabricated aluminum Alaska *steeppass* is generally available in 10-foot sections that can be transported to remote locations and assembled onsite. The highest velocities in steeppasses are lower in the water column, while the higher velocities in the standard Denil fishway are high in the water column. The location of these high velocity areas should be considered when examining suitability for target species. In Atlantic river basins, the short steeppass fishways can be effective passage for river herring, Atlantic salmon, American shad, hickory shad, and many resident *potamodromous* fish species (i.e., fish that migrate only within fresh water); however passage of American shad is comparatively more effective with a larger Denil design. The functionality of a steeppass is best adapted to small river and stream systems and dams with limited headpond and tailwater level fluctuations (Quinn 1994; Bates 2000).

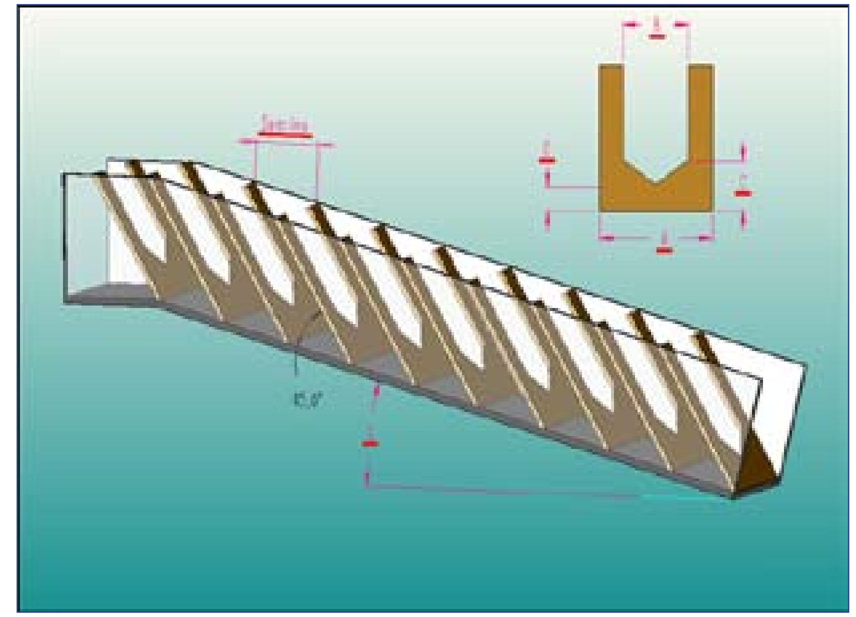


Figure 8-1. Denil fishway showing typical baffle design and nominal dimensions. *Below*: Denil fishway (4-foot width) at Potter Hill Dam, Pawcatuck River, Rhode Island.

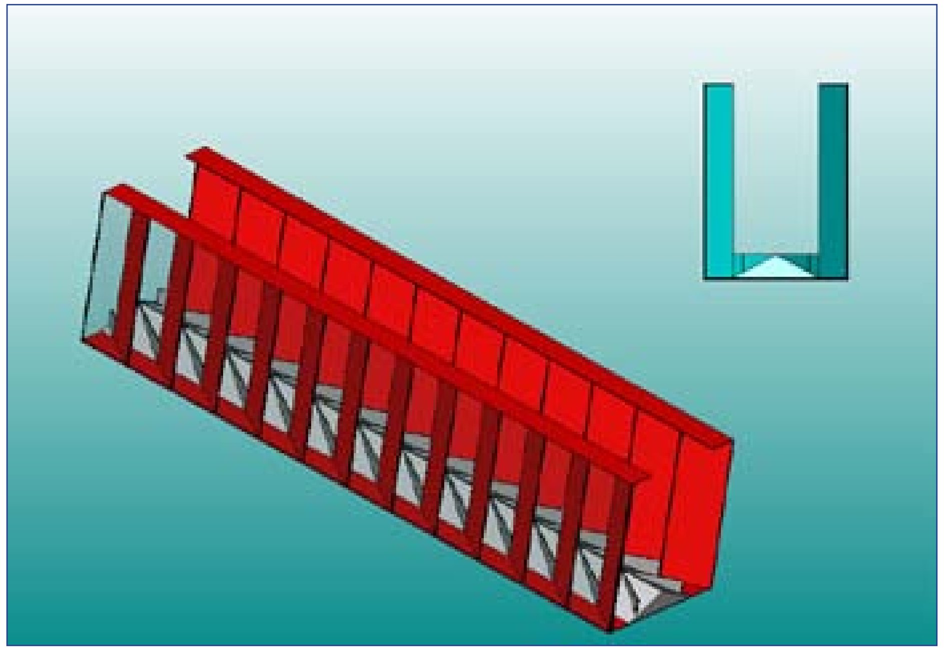


Figure 8-2. Alaska steeppass (Model A) fishway showing typical baffle design.
Below: Model Alaska steeppass fishway (18-inch width) at Mill Dam, Gilbert Stuart Brook, Rhode Island.

Denil and steeppass fishways have a similar suite of advantages and disadvantages. These qualities have been used in the decision process for selecting the type of fishway. Advantages of both steeppasses and Denil fishways include:

- Can be built of various materials, including wood, metal, or concrete.
- Relatively inexpensive to construct.

Disadvantages of both steeppasses and Denil fishways include:

- Prone to clogging with sticks and debris without regular maintenance.
- Limited tolerance for headwater and tailwater fluctuations.
- Can use too much water during low flow conditions, resulting in dewatering of upstream areas or providing too little water depth in the ladder itself.
- Need a larger minimum flow to operate compared to many pool-type ladders.
- Limitations on their length without resting pools or between resting pools may complicate design and utilization.
- In single, straight examples, sometimes the ladder entrance ends up being further downstream of the dam than would be optimal.
- In relatively deep channels, the fishway entrance is located in the upper part of the water column resulting in lesser attraction and conditions for benthic-oriented fishes.
- High energy can be problematic for weaker, smaller, adult or juvenile fishes.
- Baffles can descale, abrade, injure, or trap fish.

Pool and Weir Fishways

The purpose and basic design concept for pool fishways is to reduce the total project hydraulic head to passable increments using a series of pools and weirs, each increment comprising a carefully controlled hydraulic step. Each pool dissipates head energy to provide hydraulic conditions suitable for upstream fish movements, staging, and rest during ascent. Effective pool fishway designs commonly used in Atlantic river basins include the pool and weir fishway and the vertical slot fishway.

Pool and Weir Fishways: While pool and weir fishways are among the more common fishways employed on the Pacific Coast, mainly for adult salmonids, these fishways are less common in East Coast rivers. These fishways—when used without *orifices*—have the advantage of retaining operational effectiveness at very low flows, which is why they are often found on streams with low seasonal flow (J. Johnson, personal communication). When sufficient water is available, orifices are typically added to weir-type fishways because some fish species prefer to swim through orifices rather than swim over weirs. American shad and river herring tend to more often swim over the weirs (B. Kynard personal communication). Adding orifices, however, increases the flow requirement of the ladder and this can lead to dewatering of these ladders when used in smaller streams during low water periods. Orifices also naturally flush sediment out of the fishway and will greatly reduce maintenance of the pool. Weir type fishways are intolerant of significant headwater variations; therefore headwater needs to be well-controlled if these ladders are to be effective over the entire fish passage design flow. For example, energy dissipation requirements (4 ft-lbs/feet^{3}second) need to be conformed to, (i.e., water requirements of the weir and orifices may dictate pool volume requirements). A design diagram and photo of a weir-type pool fishway is shown in Figure 8-3.

Ice Harbor Fishways: This pool and weir design incorporates both orifices and weirs. Ice Harbor fishways were used at 1:10 slopes at their namesake, Ice Harbor Dam (located on the Snake River in Washington). The standard Ice Harbor fishway includes two overflow weirs with orifices centered below each weir and a center non-overflow weir section with baffles (Figure 8-4). This design is effective for salmonid and American shad passage in Pacific Coast rivers, including the Columbia River with a passing efficiency over 90% (J. Johnson, personal communication). This design is less commonly used on the Atlantic and Gulf coasts given the relatively higher operational flows required in comparison to other designs. The Half-Ice Harbor design has been adapted for use on smaller rivers and lower flow applications and includes a single weir and orifice, and a non-overflow wall located between pools (Figure 8-5). The Half- Ice Harbor fishway has been used effectively in Pacific Coast rivers for salmonids and American shad, though it is yet to be fully tested in Atlantic and Gulf Coast rivers.

Vertical Slot Fishways: The vertical slot fishway was first developed as a double slot design for salmonid species at Hells Gate on the Fraser River, British Columbia, by Milo Bell and C.W. Harris (Bates 1992). Detailed hydraulics of vertical slot fishways has been described by Rajaratnam et al. (1986). The original double-slot design was adapted to smaller river systems by reducing the width and using a single vertical slot. A typical diagram of a vertical slot design is shown in Figure 8-6. The vertical slot fishway is more commonly used in Atlantic and Gulf Coast rivers than the other pool and weir designs.

The vertical slot is one of the most common pool-type passage designs for American shad, river herring, Atlantic salmon, striped bass, and many other riverine fish species in Atlantic Coast rivers. Vertical slot ladders can be effective over a wide range of flow conditions. The vertical slot design is well adapted for dams with tailrace and forebay water surface fluctuations because flows within this design are self-regulating. As forebay elevations fall or rise, pool depths and flow characteristics follow uniformly throughout the fishway without the need for mechanical regulation gates, stop logs, or baffles at the fishway exit. The vertical slot pool design can be sized to effectively pass the current or anticipated daily and seasonal spawning run fish numbers. Each pool functions as a resting pool, and upstream migrating fish may spend up to 1 to 5 minutes in each pool before actively moving through the slots. The inter-pool slot width is typically 16 to 18 inches to accommodate shad and herring; earlier designs used slot widths of 10 to 12 inches, which have been effectively used for salmonids on the Pacific Coast. For American shad on the Atlantic Coast, slot width is generally no less than 16 inches. The narrow slot widths used for salmonids may result in increased fish contact, descaling, and increased mortality of American shad. The maximum head differential, usually determined for lower river flow range, establishes the design water surface profile which is parallel to the fishway floor gradient. Applications for shad and herring passage usually have a minimum water depth of 4 feet, with an average depth of 6 feet, and pool dimensions are often 10 feet in width and length. The elevation drop per pool should be 9 inches maximum for American shad and river herring (Quinn 1994). Vertical slot fishways involve more complex concrete forming, potentially resulting in higher construction costs compared with other pool and weir fishway designs.

Vertical slot fishways typically include aluminum baffle plates in the slot opening about 1 foot above the floor to create an orifice and to reduce pool turbulence. Salmonids and some other riverine species prefer to pass through the slot orifice, while American shad prefer to pass through the slot above the baffle. In recent years, the vertical slot design is being more frequently used in European rivers with excellent passage efficiency for large salmonids, allis shad (*Alosa alosa*), and cyprinids (FAO/DVWK 2002). Often the European designs include rock substrate imbedded in the concrete floor of the fishway, to provide additional energy dissipation, and to provide lower flow velocity conditions for benthic-oriented fish, or small fish with low swimming speed performance (Figure 8-7).

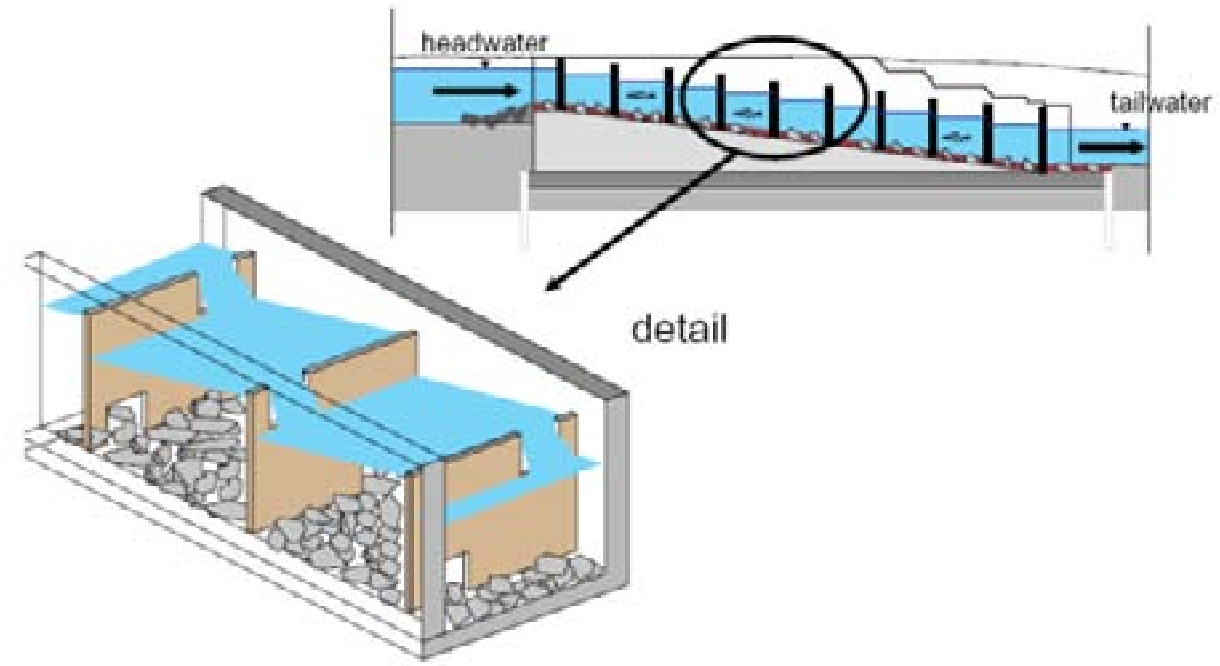


Figure 8-3. Pool and weir Fishway. *Above:* Pool and weir fishway design, FAO (2002). *Below:* Pool and weir fishway designed by Marshall McDonald and installed circa 1905 on the Blewett Falls Dam, Pee Dee River, North Carolina. This fishway is no longer functional and was not successful in passing American shad.

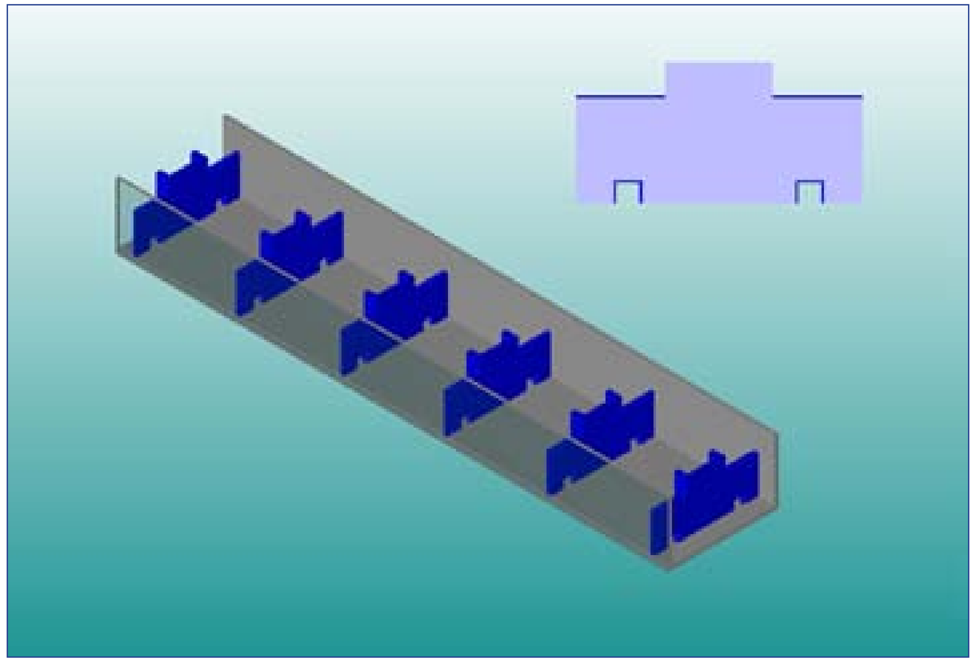


Figure 8-4. Ice Harbor fishway design. *Below*: Ice Harbor fishway (16-foot pool width); Turners Falls Dam, Connecticut River, Massachusetts.

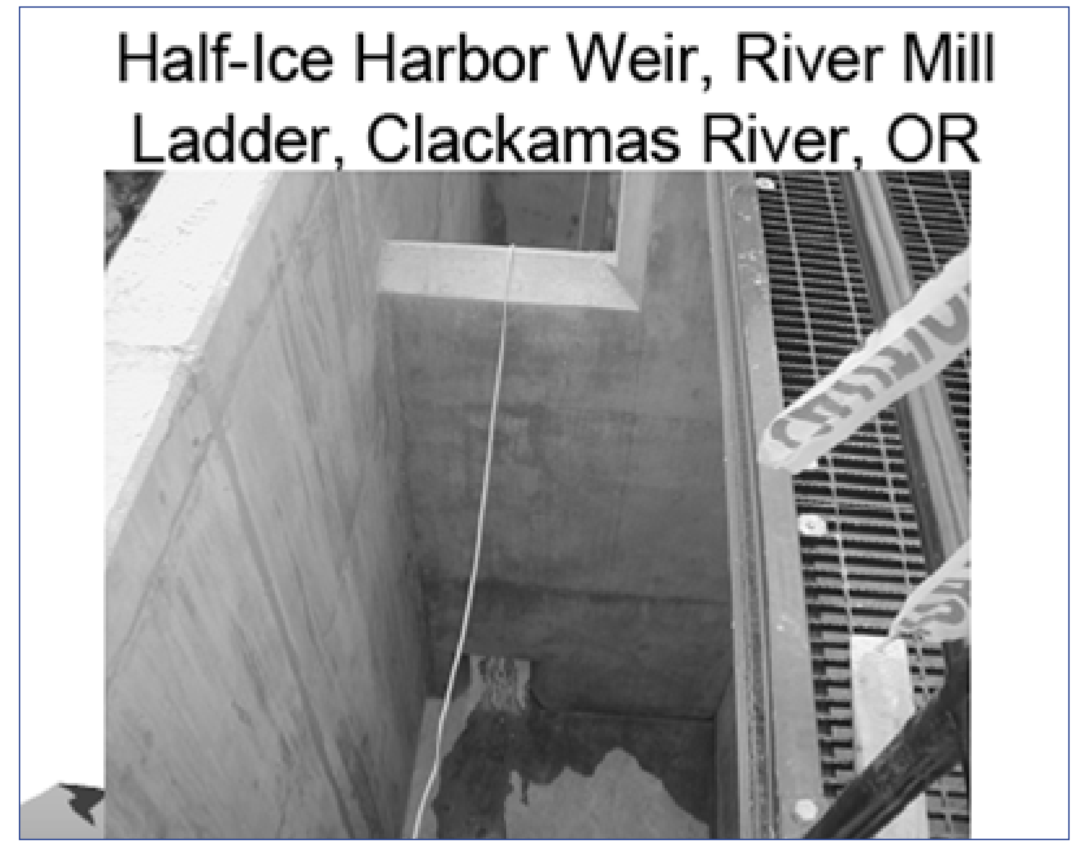


Figure 8-5. Half-Ice Harbor fishway.

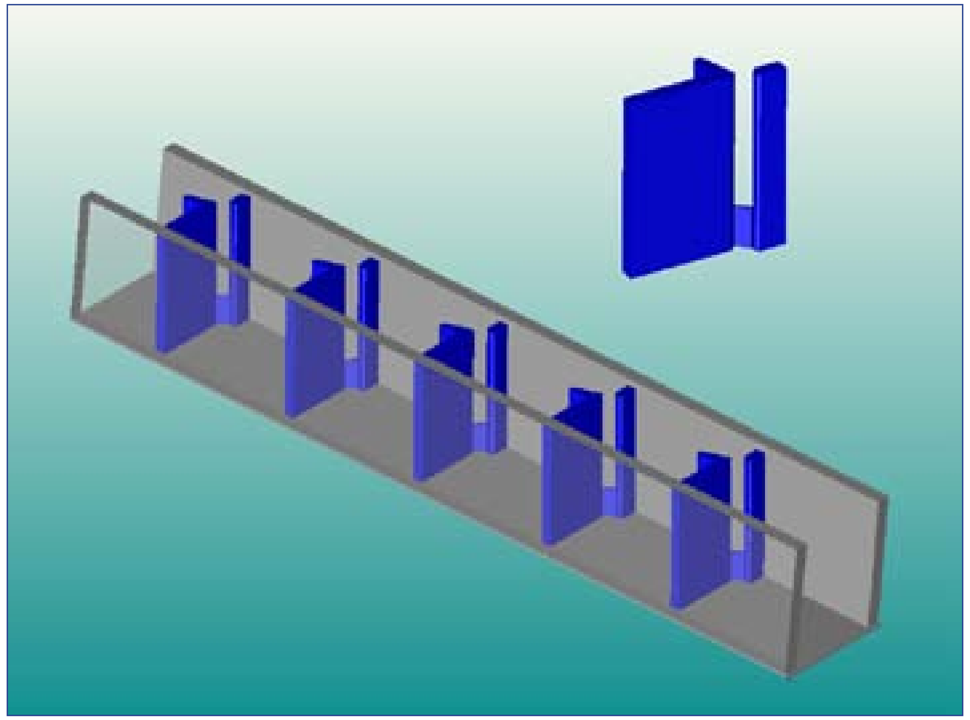


Figure 8-6. Vertical slot fishway design, with single slot. *Below*: single-slot vertical slot fishway (8-foot pool width); Veazie Dam, Penobscot River, Maine.

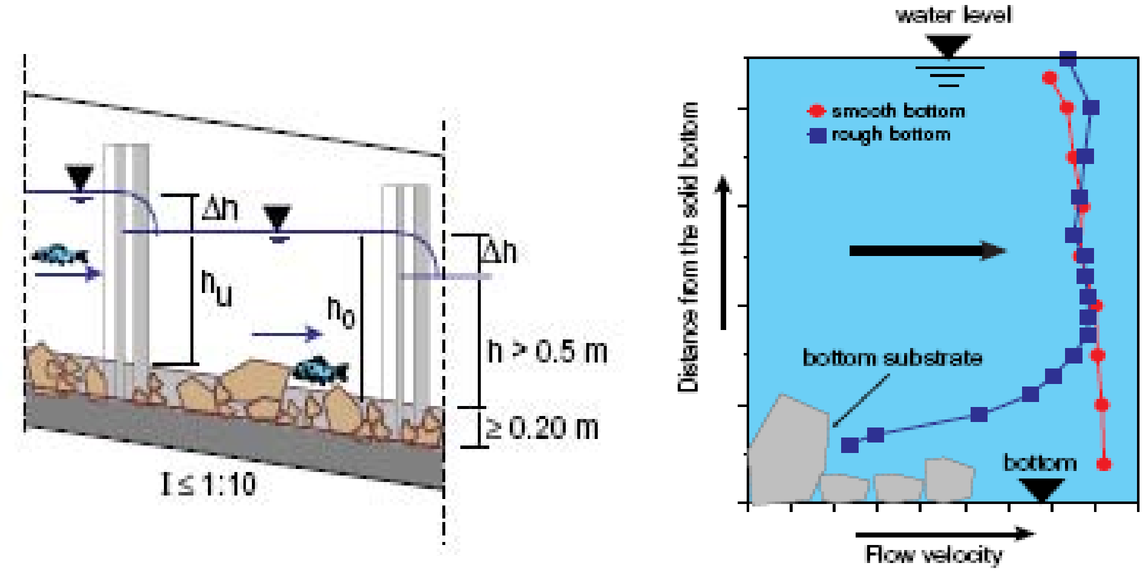


Figure 8-7. Slot fishway with rocky substrate installed to improve upstream passage of smaller fish species. *Right:* Diagram showing velocity distribution in the slot comparing smooth and rough bottom substrate. *FAO/DVWK 2002*

Serpentine Offset Wall Fishway: This fishway design has design criteria similar to the vertical slot type, with the potential to provide adequate energy dissipation at higher design slopes, or to allow passage of many species with lower attraction flow discharges (Figure 8-8). The serpentine fishway design was originally developed as a regulating section for the John Day Dam (Columbia River, Washington) pool and weir fishway in the late 1960s. Passage of American shad through the original orifice-type regulating section was impaired by reluctance of shad to pass through submerged orifices at non-overflow weirs; studies of shad behavior indicated shad would pass more readily through a full-depth vertical slot with relatively low slope. A new full-depth vertical slot design was then developed for shad that would be self-regulating and allow a large, full-depth zone of passage between weirs (Johnson and Perkins 1968). Construction of the new regulating section at John Day Dam using the serpentine design had demonstrably better performance for shad passage than the original orifice-type regulating section (Weaver et al. 1972; Monk et al. 1989).

In subsequent years, the serpentine design has been implemented at larger pool-type technical fishways where headpond or tidal variation in water levels is high, including the upper section of Vernon Dam fishway on the Connecticut River in Massachusetts. In some instances, the entire length of a fishway has been constructed with the serpentine design (e.g., the Charles River Dam fishway in Boston, Massachusetts) to accommodate high variations in tailwater level at this tidal site (USACE 1977).

Typically, serpentine fishways are constructed for shad with a low overall slope of 1:15, and up to 1:10, with a drop per pool design range of 9 inches. In addition to the full depth slot with a relatively wide width, these features result in qualities which are thought to be favorable for shad passage, including relatively low water velocities through the slot, low flow separation and reduced entrainment of air. A few evaluations have been performed on passage of shad and salmonids through serpentine fishways, indicating passage is relatively high for these species; however rigorous quantitative passage data are lacking for this design. The low slope and large pool size of the serpentine design also dictates a relatively long fishway for a particular elevation gain, and transit times through this fishway design may be relatively high. Nonetheless, the large pools offer adequate low-velocity resting space for ascending fish at any point within the fishway, so transit time issues may be less critical for this design compared with other pool and weir designs. These features also usually dictate cost of construction and a large required areal footprint.

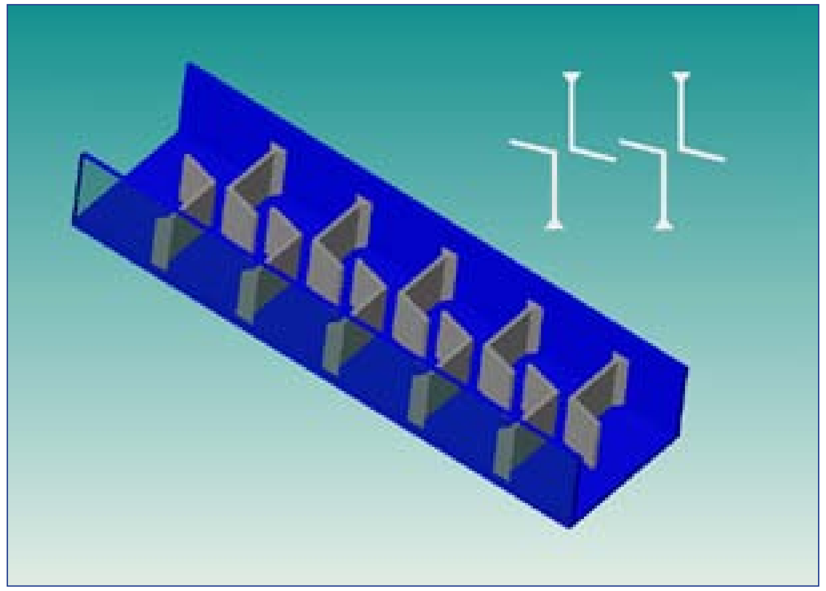


Figure 8-8. Serpentine or offset-wall fishway design. *Below:* Serpentine fishway (20-foot pool width); Vernon Dam, Connecticut River, Vermont.

Application

Anguillid eels are catadromous species with special requirements for upstream passage. As catadromous fishes, juvenile eels recruit to freshwater habitats as small, post larval glass eels or elvers. Eels then migrate long distances, often hundreds of kilometers, into watersheds. Passage may be required at many barriers within a watershed, and the size of eels to be passed can range from 50 millimeters to over 900 millimeters total length.

The small size and limited swimming capabilities of juvenile eels, which is the primary upstream migratory life history phase, usually necessitate some type of structure for upstream passage. Although larger eels may use conventional technical fishways to some degree, most small eels have difficulty using traditional fishways because water velocities and turbulence limit upstream progress (Baras et al. 1994). Eels can potentially use conventional fish lifts and locks, but their performance is either inefficient or unknown. Typically, crowders and retention screens used in traditional fish lifts are too coarse and allow an eel to pass through, which limits conventional fish lifts as practical eel passage devices.

Juvenile eels are capable of swimming through closed conduits, if water velocities within the conduit are low and not too turbulent, and can utilize roughness to gain leverage to assist in movements through narrow cracks or interstitial spaces in gravel or cobble substrates (Barbin and Krueger 1994). Similarly, juvenile eels can crawl over open wetted surfaces, with small eels of about 150 millimeters total length or less adhering to structures mainly by surface tension. Although these behaviors are largely responsible for the presence of eels upstream of barriers with no fish or eel passage structures, the efficiency of eels in passing barriers by these methods is probably low. Factors that may contribute to reduced passage efficiency, absent a dedicated eel passage facility, include structure irregularities and overhangs, predation, slope of the structures, and water source limitations. The efficiency of passing larger juvenile eels can be improved by provision of roughened or specially-designed vertical cylinder, knobbed, or brush substrates (Solomon and Beach 2004b). The crawling behavior of eels is demonstrated at many ramp structures installed at small and moderate size barriers (e.g., eelways installed at the Orono and Stillwater Projects on the Penobscot River, Maine; Burnham and Benton Falls Projects on the Sebasticook River, Maine).

Additional detailed information on eel upstream migratory behavior and passage structures can be found in Clay (1995); FAO/DVWK (2002); Knights and White (1998); Porcher (2002); Solomon and Beach (2004a, b); and Tesch (1977).

Operational Design

Selection of an appropriate design for an eel pass structure is dependent on habitat, eel size, and life history stage of the eels to be passed. The size range of eels at a site can vary greatly, even for sites at a great distance inland from the ocean; therefore auxiliary purpose-designed passage structures are typically used. Occasionally a simple structural modification to a barrier has been implemented by roughening of the downstream face of a dam or other barrier surface to enhance climbing of eels directly over the barrier, or with addition of climbing substrates (e.g. commercial plastic materials, prefabricated concrete roughening elements, netting) to the dam face to facilitate direct climbing. These solutions are generally only practical for low-head dams (less than about 6 feet) to minimize the climbing distance and exposure to predators. Modifications to the barrier or addition of climbing substrates are not typically considered for sites where significant headpond fluctuations create either insufficient or too much flow over the substrate (or damage the substrate at high flows). In some instances accommodation can be made for minor headpond fluctuations by tilting the roughened surface of climbing channel laterally at the dam crest. Such laterally sloped channels can accommodate high velocity attraction flow through the invert (lowest point) of the channel while maintaining an adjacent low velocity wetted margin through which eels can climb (Figure 9-1).

At smaller sites, a Delaware-type pass can be constructed by boring a hole through flashboards or the dam crest and stuffing trawl netting or other material into the hole. Netting leading to the hole can then be placed over the dam face, providing a wetted, roughened route for eels to ascend and pass the dam (Figure 9-2). However, Delaware-type passes suffer from frequent clogging by debris, require extensive maintenance, have limited flow capacity, and may not be attractive to the eels.

The most common eel pass design is the *ramp-type*, which commonly employs a level, open channel ramp supplied with attraction flow at its entrance, with a small amount of flow directed down the ramp to create a constantly wetted climbing surface (Figure 9-3). Water depth over the wetted ramp is carefully balanced to accommodate ascending eels while preventing flushing of small eels down the ramp by excessive flow. The ramp channel is usually modified with a roughened substrate to enhance climbing and the substrate needs to be carefully matched to the size range of eels to be passed at the site to avoid size-selectivity of the pass. Designing the slope of the ramp should take into consideration water flows that promote passage efficiency; typically, the maximum slope for effective passage is dependent on the substrate used (Table 2). Eels attracted to the ramp entrance locate the ramp and begin to climb, seeking the source of flow and ultimately a route to pass the barrier. The ramp can either extend to the full height of the barrier and exit directly to a headpond (*full-height ramp pass*) or terminate at a trap box which eels enter (usually by dropping from the upper end of the ramp) and are retained until they can be collected and physically transported (e.g., by bucket or truck-mounted tank) above the barrier (*trap ramp pass*). Some design variations of the trap ramp pass employ an automated or semi-automated lifting system to lift the trap box to the top of the barrier and empty the box into the headpond (a variant design sometimes termed an *eel lift*).

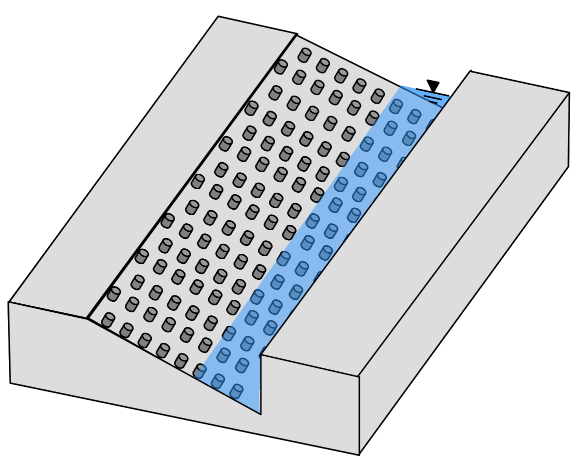


Figure 9-1**.** Ramp-type eel pass that employs a lateral slope to provide a constant wetted margin along the climbing substrate under conditions of low (left figure) and high (right figure) headpond levels.

Figure 9-2. “Delaware”-type eel pass utilizing PVC pipe routed through flashboards on dam crest, with trawl netting stuffed through pipe and over dam face, Leesville Dam, Salmon River, Connecticut.

				Brush/ Stud Dimensions					
Type	Manufacturer	Model	Material	Bristle Tuft/ Stud Diameter (mm)	Bristle Tuft/ Stud Spacing (on-center; mm)	Height (mm)	Max. ramp slope (deg.)	Eel size range (mm TL)	Notes
Geotextile mat	3M, USA	Enkamat 7220	polyamide	n/a	n/a	20	60	50-150	Prone to clogging with debris, algae
Bristle substrate	FISH-PASS, France	Brush substrate	polypropylene	4.5	14	70	45	100-350	
Bristle substrate	FISH-PASS, France	Brush substrate	polypropylene	4.5	21	70	45	>300	
Bristle substrate	FISH-PASS, France	Brush substrate	polypropylene	4.5	14 & 21	70	45	60-350	"hybrid" substrate of 2 brush spacings
Stud substrate	FISH-PASS, France	ABS domes	ABS plastic	32	48	30	30	>135	
Stud substrate	Milieu, Inc., Canada	"Eel Ladder"	ABS plastic	31.2	63.5	38		<150	
Stud substrate	Milieu, Inc., Canada	"Eel Ladder"	ABS plastic	50.8	80	114	55	150-800	
Stud substrate	American Wick Drain, Inc., USA	Akwadrain	Polystyrene	16	31.7	24	45	150-300	Temporary passes only; brittle, short life

Table 2. Sources, dimensions, and application data for various commercially-available eel pass substrates.

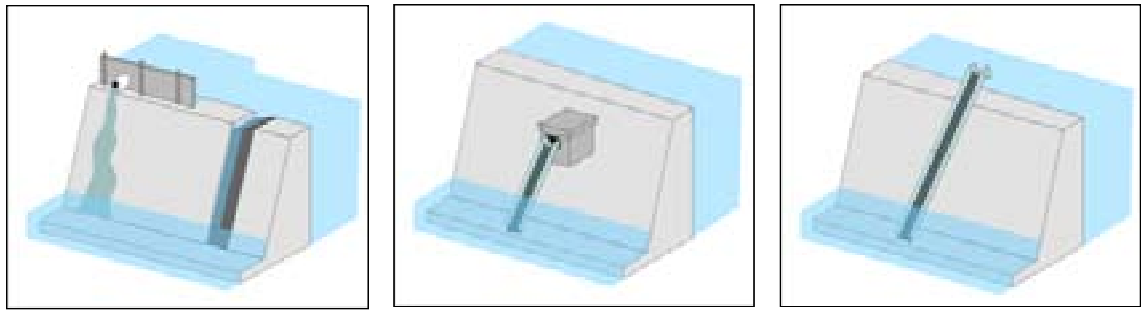


Figure 9-3. Basic designs for climbing -type eel passes at low- to moderate-head dams. *Left:* Delaware-style pass (left side of dam) with pipe installed through flashboards and netting or other climbing material draped over face of dam; integral ramp pass (right side of dam) with substrate embedded into channel cut into dam crest and face, with lateral slope to accommodate minor fluctuations in headpond. *Middle:* Short ramp pass with eels exiting into trap box (usually installed at dam ends or abutments for access and protection from spill flows) (after Solomon and Beach 2004b) *Right*: Ramp pass extending to full height to dam, with eels exiting ramp directly into headpond.

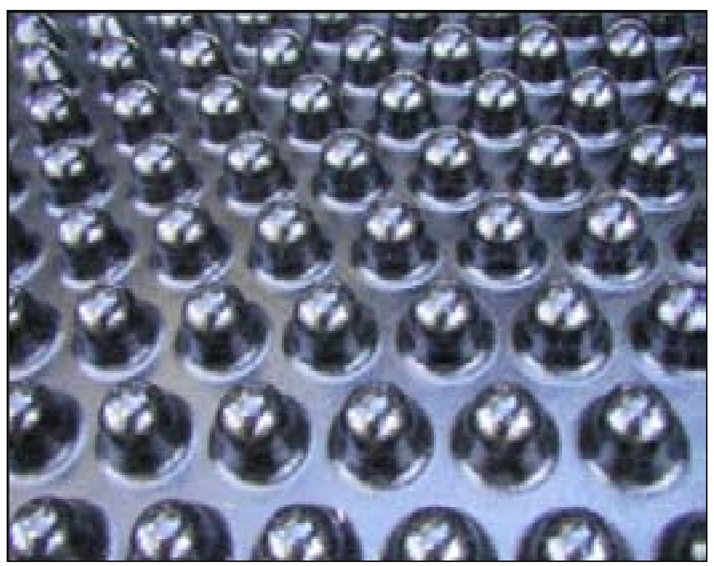


Figure 9-4. Example eel pass substrates. *Above Left:* Plastic PVC pipe substrate, Roanoke Rapids Dam eel pass, North Carolina (with eels ascending). *Above Right:* Experimental plastic by Fish Pass Company in France. *Bottom Left:* Bristle substrate with nylon bristles and polypropylene base, also by Fish Pass.

Figure 9-5. Partial height ramp trap. *Below:* Full height ramp, Roanoke Rapids Dam, Roanoke River, North Carolina

For larger eels, greater than 300 millimeters in total length, traditional technical fishways (e.g., baffle or pool-and-weir type) have been used as a means for passage; however, these structures have not been extensively evaluated and their overall performance is unknown. To pass larger eels, maximum velocities in technical fishways should be relatively low, which implies a very low slope and/or drop per pool, usually making them an impractical passage solution. Retrofits of technical fishway designs (e.g., addition of bottom substrates in pool-and-weir fishways) may be possible to enhance their performance, but these types of retrofits have not been extensively tested. Eel passes typically use a vastly smaller amount of flow than traditional fishways. As a result, eel passes are strongly affected by competing flow; primarily spill and turbine flows, but also dam leakage, cooling water outfalls from turbine units, and downstream bypass flows. Under conditions where competing flows are significant, eels may find it difficult to locate an eel pass, or approach a pass entrance if flows in proximity to the pass have high velocity or turbulence. Upstream eel movements may also be influenced by environmental conditions; typically eels initiate climbing behaviors at night at temperatures above 50°F, and movements may increase during rain events.

Structural Design

Siting of eel passes is a critical component to their success, due to the aforementioned issues of competing flows. A preliminary survey for the presence of eels at a site (at night, via foot, boat, or snorkeling) is important to locate natural points of concentration of eels, which can become candidates for locations of eel pass entrances. Typically, feasible sites for eel passes are limited due to restricted access or the need to protect smaller, more fragile eel pass structures from high water levels, velocities (e.g., spill flows), or debris. In many cases, sites that are appropriate for traditional fishways may also be appropriate for eel passes. But it also is common for eels migrating upstream to concentrate at alternate sites, such as below points of dam leakage, spillways, gates, “climbable” rock ledge, that have some degree of water flow. Areas where water is quiescent, yet as far upstream as possible (i.e., corners of tailraces, below dam/spillway abutments), are typically good candidate locations for eel pass entrances when natural points of eel concentrations are unknown. Likewise, locating eel passes near zones of high velocity, wave action, or turbulence would make it difficult for small eels to find or enter an eel pass entrance.

Design Criteria

Primary design criteria for eel passes depend on the size of the site and height of the dam, and capacity of the pass. Larger rivers/dams may require multiple passes and ramps or lifts with greater attraction flow. Smaller rivers or rivers with expected low numbers of eels may only require single, smaller passes. Although full-height ramp passes have been constructed for dams over 230 feet in height, it is recommended that dams of a very high head height employ trap ramp passes or eel lifts to avoid extensive stress from protracted climbing (Solomon and Beach 2004a). Design criteria for eelways are dependent on site characteristics, dam height, river size and flow, and swimming capabilities of target fish species. Below is a list of some design criteria used in planning eel passage based on field experience and information within Solomon and Beach (2004a, b).

For Ramp Passes:

- Ramp width should be 10 inches to 3 feet (larger for very large dams or required higher capacities).
- Ramp length is dependent on slope; vertical height of straight runs of ramp should be limited, suggested 10 feet in total vertical height per run.
- Ramp cover should be a full opaque cover for entire width/length of ramp, except open above high water level at entrance.
- Resting pools should include a width equal to the ramp, and the minimum length of 1.5 feet. May be fitted with climbing substrate; no minimum depth (can be “flat” sections of ramp).
- Ramp flow typically provides 1 inch of flow depth over the climbing substrate.
- Attraction flow is dependent on size of pass and presence of competing flows; typically 80 to 300 gallons per minute.
- Trap flows should be adequate to maintain sufficient oxygen and ambient water temperatures.
- Frequency of trap clearing of eels should be daily if possible; no longer than every 2 to 3 days. It is highly recommended to clear the trap when it reaches 50% capacity.

For Eel Lifts:

- Lift bucket capacity should generally have a minimum volume of 13 gallons and capacity and flows per traps as listed above.
- Lifting frequency is dependent on bucket capacity; daily at minimum. Lifting required at 50% bucket capacity at a minimum.

Chapter 10. Considerations for Sea Lamprey Passage

Passage of sea lamprey has historically been of low priority for Atlantic Coast barriers, primarily due to the low recreational and commercial fishery value of the species and concerns for introduction into non-historical habitat. In recent years, the ecological importance of the lamprey in coastal and riverine waters has become more broadly understood (refer to Chapter 2). Experience has shown that traditional technical fishways will pass sea lamprey to a limited degree, yet there are few directed studies of traditional fishway passage or efficiency for sea lamprey. Passage of the morphologically and behaviorally similar Pacific lamprey (*Lampetra tridentata*) has been shown to be inefficient in large technical fishways of the Columbia River (Moser et al. 2002).

Sea lamprey are not particularly strong swimmers but have the capability of sprint swimming for short durations, and can also leap and swim at the surface with a large portion of their body above water, which reduces drag. Their ability to attach to substrates with their oral disk and remain attached for long periods under high velocities allows sea lamprey to incrementally progress through turbulent or high velocity environments via bouts of sprint swimming and attachment, which they would not normally be able to progress against via free swimming alone (Adams and Reinhardt 2008). Sea lamprey can also "climb" smooth wetted surfaces by inching forward using contraction of their oral disks, while remaining attached. This behavior is commonly employed on smooth, wetted surfaces, and can be accomplished with the body largely out of the water, as long as the gills remain wetted. The "alternating" swimming, climbing, and attachment behaviors probably account for the ability of sea lamprey to ascend a wide variety of passage structures and hydraulic environments.

Sea lamprey passes structures primarily at night (Haro and Kynard 1997), but some passage also occurs during the day. They can spend long amounts of time in passage structures, and can accumulate in large numbers within resting pools or other low-velocity zones, which may hamper passage of other fishes.

Because adult sea lamprey are *semelparous* and die after spawning, downstream passage protection for post-spawning adult sea lamprey is not necessary. Juvenile sea lamprey migrate downstream primarily in the fall and early winter months and are usually not considered for protection from turbine entrainment and mortality. Turbine mortality or injury studies for sea lamprey are not available. It is expected that juvenile downstream migrant sea lamprey are likely susceptible to turbine and impingement mortality given their anguilliform body morphology and their relatively weak swimming ability[1].

1 Research on juvenile sea lamprey is limited. Observations of juvenile sea lamprey swimming ability by S. Gephart, CT DEP, are noted in Kircheis (2004). However, specific data on swimming ability are not included.

Chapter 11. Fish Passage at Navigation Locks

Application

Navigation locks and dams were originally designed to improve commercial vessel navigation and transportation of agricultural and industrial products in major rivers. Navigation locks generally were not designed to accommodate fish passage; however in many cases lock operations can be adapted to provide fish passage for many species, particularly alosines. A key factor with potential for providing fish passage at a navigation lock is attraction flow. Flows through most navigation locks are relatively low and intermittent, and fish attraction flow is usually limited. Navigation locks are also usually sited some distance from dominant attraction flows at a dam (i.e., tailrace or spillway), thus initial guidance and attraction to navigation locks can be hampered. Navigation locks have been considered as passage devices, but a preliminary performance/efficiency evaluation of navigation locks is usually required. In the northeastern U.S., existing locks that are used as primary upstream passage facilities include the Charles River Lock and Dam on the Charles River, Massachusetts, and the Springs Island Dam as a component of the Cataract project on the Saco River, Maine. Incidental fish passage occurs at the Green Island Lock and Dam on the upper Hudson River in New York[1] and the State Barge Canal on the Mohawk River in New York. In the southeastern U.S., examples include the Pinopolis Lock and Dam on the Cooper River, South Carolina (Figure 11-1); the New Savannah Bluff Lock and Dam on the Savannah River near Augusta, Georgia; the Jim Woodruff Lock and Dam on the Apalachicola River, Florida; and the Cape Fear Lock and Dam on the Cape Fear River, near Wilmington, North Carolina.

Operational Design

Navigation Locks

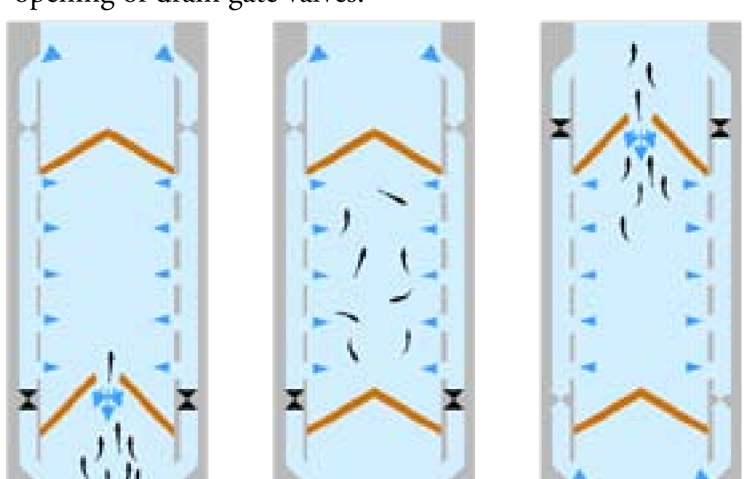
The concept of passing fish through locks involves attraction of fish from a tailrace or spillway into a lock (usually with attraction flow), trapping fish within the lock chamber, closing the downstream end of the lock chamber, filling the lock to the headpond level, and releasing fish to the headpond. Release of fish is accomplished either by opening upper lock gates (lock chamber drains can also be opened simultaneously to establish a modest directional flow through the lock, effectively "attracting" fish out of the lock), or by simply fully opening upper lock gates and allowing fish to exit by wandering out of the lock structure. The navigation lock cycle time varies from 20 minutes to hours depending on the size of the lock facility and the height of the headpond above the tailwater area.
Little or no structural modifications from the original navigational design are usually made to provide fish passage at navigation locks. Operational changes that have been utilized at locks along the Cape Fear River, North Carolina, for example, include adjustment of upper and lower navigation lock gates to control flow velocities and create appropriate flow fields to encourage fish to move into the lock, and to exit upstream. For attraction flow, the navigation lock fill system can be used to help provide sufficient flow conditions. Gate or lock fill and drain valve structures also should be carefully operated to avoid damage to fish during the lock operating (opening/closing) cycle. In general, locks can potentially be efficient fish passage structures if they are designed to pass a significant amount of flow (either as internal flow or attraction flow) in relation to total river flow to maximize attraction and retention of fish within the lock and incorporate operational plans to accommodate the migration season. However, this is a rare situation at most barriers unless existing navigational locks have enough operational flexibility to be modified and/or operated as passage structures including additional operational cycles to pass fish even when no vessels are transiting the locks. Locks may also be designed to include crowder devices to enhance entry into the locking chamber (Travade and Larinier 2002).

1 Twin Denil fish ladders are planned for the Green Island hydropower project in accordance with the 2009 Relicensing Settlement Agreement for Fish and Wildlife Issues.

Criteria for Navigation Locks

No specific design and operation criteria exist for retrofitting existing navigation locks to pass fish; lock operation is usually dependent on site-specific design of the lock and constraints with respect to allowable cycle times and fill-drain rates. To facilitate timely fish passage, locks should be operated as frequently as possible to maximize attraction to and retain fish in the vicinity of the lock entrance, and minimize delays in upstream movement. Important considerations include entrance velocities that attract and allow fish to pass into and out of the lock, but do not create a velocity barrier. Lock gate openings should be as wide as possible to permit large target species to enter, as well as entire schools of fishes (e.g., alosines). Efforts should be made to prevent or minimize fallback of fish through drain gates or other drain structures, either via minimizing water velocity in the vicinity on drain openings or with adequate screening. Designs to retrofit fish passage at existing locks should also be built with adequate capacity both with respect to accommodating numbers of expected fish and adequate flow during the locking cycle to ensure sufficient dissolved oxygen levels and ambient water temperatures.

Figure 11-1. Pinopolis Navigation Lock, Cooper River Dam, Cooper River, South Carolina. *Below:* Operation of a typical navigation lock for fish passage. *Left*: opening of downstream lock gates to allow fish to enter. Flow is regulated by drain gate valve opening; fish are attracted to flow jet through opening in gates. *Middle*: Closing of both lock gates and filling of lock. *Right*: opening of upstream lock gates, flow through which can be enhanced by opening of drain gate valves.



Application

Fish Lifts

Fish lifts, also known as elevators, are electro-mechanical fish passage devices generally installed at hydropower dams with heads greater than 25 feet as a cost effective option associated with large and/or long technical fishway structures. Lifts are mechanical devices requiring electrical power on-site, with higher maintenance and operation costs as compared to volitional technical fishways. Fish lifts are often used at sites where space is limited or site constraints do not otherwise permit construction of a traditional volitional fishway. While fish lifts can be automated, they usually require personnel on-site and regular maintenance and inspections.

Fish lifts can be scaled appropriately to sites at moderate to large rivers; they are usually not cost effective at smaller rivers. Multiple lifts at dam sites can also be constructed to increase capacity and efficiency or to include additional target species.

Fish Locks

Fish locks are similar in design to fish lifts, but the elevator component for lifting fish from the tailwater entrance to the exit channel at the headpond is filled with water. Fish locks are rare along the Atlantic seaboard in comparison to technical fishways and ladders due to relatively high construction and operational costs. Two examples in the northeastern U.S. include locks at the Springs and Bradbury dams at the Cataract Hydropower Project on the Saco River, Maine. An example in the southeastern U.S. is the St. Stephen Fish Lock (generally referred to as a fish lift) at Lake Moultrie on the Santee River. Fish locks were originally designed and somewhat successfully used for passage of adult salmonids, primarily in Europe (Clay 1995; Travade and Larinier 2002). Fish locks were also employed on the Pacific Coast at the Bonneville Dam on the Columbia River and proved to be effective for passage of salmonids and for white sturgeon (*Acipenser transmontanus)* (Warren and Beckman 1993). The Bonneville fish locks were later replaced by Ice Harbor fishways that proved to be more effective for higher priority salmonid species (E. Myer, personal communication). Fish locks can either be open-channel structures with the locking chamber open to the atmosphere; i.e., similar in design to navigational locks yet "scaled down" to accommodate a given capacity of fish, or closed conduits (e.g., "Borland"-type fish locks), where fish are guided to swim up a closed pipe or other conduit from the foot of the dam to the headpond. Both designs utilize attraction of fish into an entrance or other collecting structure, usually via supplementary attraction flow. Presently, fish lock facilities are typically not constructed at most high-head dam sites in favor of fish lifts, which can be less expensive to build and operate.

Operational Design of Fish Lifts and Locks

Fish lifts operate by first attracting fish to a channel at the base of a dam; fish attracted into the channel are then guided to a square or rectangular hopper or lift hopper and retained by a screen just upstream of the hopper (Figure 12-1); older designs used a "finger trap" mechanism to prevent fish from exiting an entrance channel (Clay 1995). During the lifting cycle, the hopper may be raised directly under the fish, or movable crowder screens are closed behind the fish, which then move upstream to crowd fish into position over the submerged hopper. The lift hopper assembly may also be equipped with an attached sloping floor brail (screen) that concentrate fish into the hopper when it is first raised. The lift hopper is then raised to headpond level and fish are sluiced from the hopper (by tipping or via a drain gate) directly into a headpond, an exit channel leading to the headpond, or transport truck. Counting facilities (e.g., counting windows) may be constructed as part of the exit channel structure. The hopper may also make a stop and dump at an intermediate level for sampling of fish or trucking. After releasing the fish, the hopper is lowered to the tailrace level and the cycle repeats.

Lifts may be operated via hydraulics, but more typically via an electric hoist and counterweight mechanism. Cycle times of lifts can vary from every 15 minutes to one or two lifts per day; modern lifts equipped with a high speed electric hoist can cycle within a few minutes. Lifts can be automated, but are usually manned during operation. Lifts also require attraction water systems via pipes or gravity-fed channels. Volume flow for attraction water can be large for larger lifts, and is typically comparable to attraction water flows for large technical fishways.
Fish lift entrances typically operate under varying tailwater levels between the 5% to 95% exceedance flows. Fish lift operations can cease when flows are outside these levels. High tailwaters during flood events may inundate the attraction water channel and crowding mechanism, rendering the lift inoperative. Generally, lifts operate under a narrow range of tailwater levels.

Hoppers are usually sized in accordance with the species to be passed and number of fish expected to be lifted during the peak of the run for a design population (e.g., target population for management goals). Typical hopper volumes range from 35 to 700 cubic feet (Travade and Larinier 2002; Rizzo 1994).

Lifts may also suffer from "fallback" or delay problems similar to other fishway facilities. Fish may be reluctant to immediately move out through the lift exit channel into the upstream reservoir, or location of the exit too close to the hydropower turbine intakes. Delay issues resulting from operations are usually addressed in the design phase.
Operation of fish locks is similar to lifts described above; however as fish are moved into the lock by the crowder system, the lock gate at the downstream end of the lock chamber is closed and the lock is filled with water to the headpond level. Fish locks of open-channel design move fish vertically to the headpond level either volitionally or via a brail or false floor that "herds" fish to the outlet. The fish are released into an exit channel to the headpond (Figure 12-2). The exit channel generally includes a fish viewing window or counting station similar to the fish lift design. Both open channel and closed-conduit locks utilize mechanical closing mechanisms (gates or valves); in the case of closed conduits, the lower closing mechanism must be able to withstand pressures equivalent to the total hydraulic head of the dam. Fish passage cycle times for a fish lock often are approximately 15 minutes.

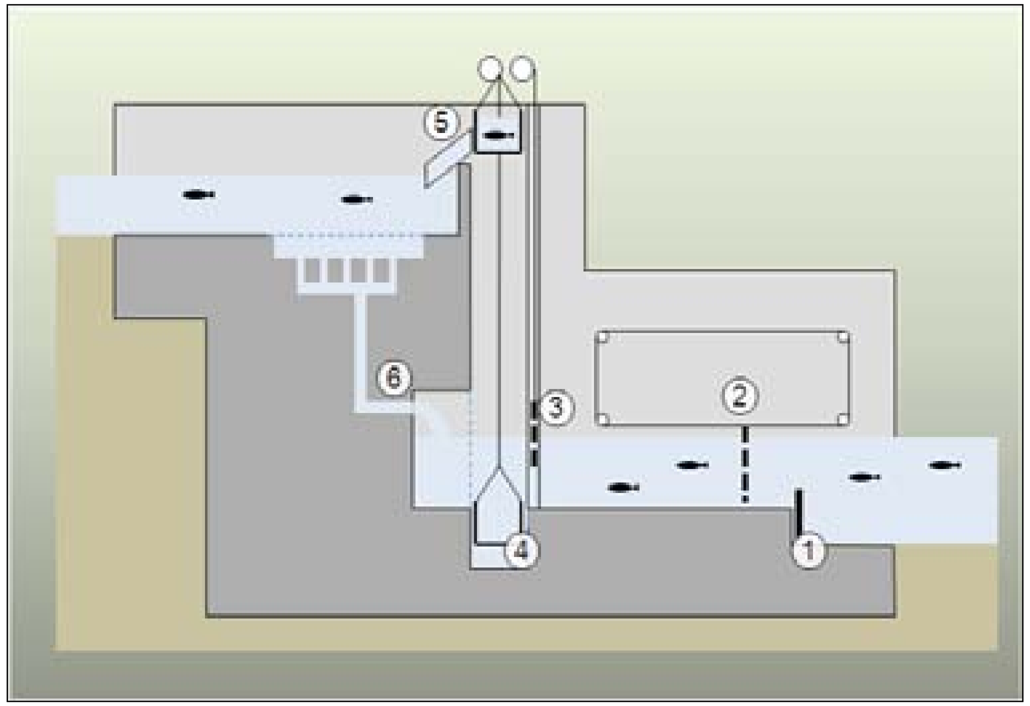


Figure 12-1. Fish lift diagram. 1: flow control gate; 2: movable crowder; 3: confinement screen; 4: lifting hopper; 5: dump chute; 6: attraction water system. *Below*: Cataract Falls Fishlift, Cataract Falls Dam, Saco River, Maine.

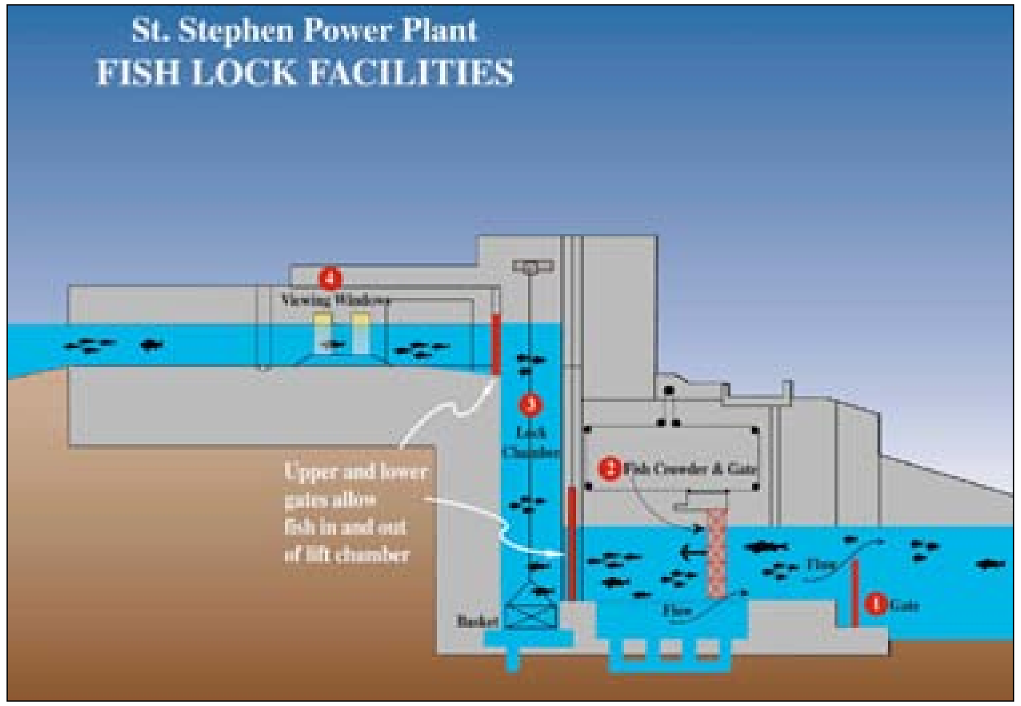


Figure 12-2. Design diagram for the St. Stephen Fish Lock. *Below*: Aerial view of the St. Stephen Fish Lock, showing the entrance and exit to the right of the tailwater area, St. Stephen Dam, Santee River, South Carolina.

Structural Design of Fish Lifts and Locks

The superstructure of fish lifts is typically constructed from structural steel with concrete walls and foundations at tailwater level and concrete or non-corrosive metal (galvanized or stainless steel or marine aluminum) exit channels and steel or plastic attraction water piping. Size and strength characteristics are dependent on the overall size, vertical lift, and hopper capacity. Fish lock "elevator" chambers are generally constructed with concrete, and include upper and lower mechanical gates with water tight seals to prevent leakage of water during the lock cycle.

Experience at fish lifts and locks identified sizing of retention and crowder screens to be critical; typically screens are sized small enough to retain all sizes of target species, but not damage fish by entrapment between screen meshes or impingement (e.g., fish impinged on crowder screens by high attraction water velocity). At the same time, screens should have low enough head loss to maintain minimum attraction flows. Debris loading affects functional performance of screens; typically attraction water is screened at an intake before entry into a lift structure.

Exit channels are generally sized commensurate with the capacity of the lift (i.e., avoid crowding when the lift is transporting fish at a high rate), with adequate flow and water turnover to ensure high survival of fish, as well as guidance of fish to the channel exit by directional flow (see also Chapter 7, *Fish Counting Stations*). Exit channels are also designed to accommodate fluctuations in headpond level without appreciably influencing channel flows or provision of attraction water.

Fish lift hoppers frequently concentrate large numbers of fish during the lifting cycle, therefore the hopper is typically designed to ensure minimal stress and damage to fish as they are lifted in high numbers. Below are some considerations to ensure the hopper facilitates safe passage.

- Some provision of auxiliary water while lifting may be necessary.
- The hopper sluicing mechanism should be rapid and non-injurious to fish.
- Sidewalls and floors should be smooth and interior corners rounded to a degree.
- Sloped floor in the hopper to permit rapid release of fish without stranding inside the hopper once all the water has drained.

Fish locks typically have a metal brail or basket composed of perforated stainless steel or aluminum plates with smooth surfaces, and a cable mechanism to lift the basket up from the base of the lock to release fish into the exit channel.

As with technical and volitional fishways, attraction is a key element of the overall performance and efficiency of fish lifts and locks. Typical attraction water systems are sized similar to large fishways for sites of equivalent size and flows.

Performance of Fish Lifts and Locks

Fish lifts and locks are frequently used for passing large runs of a variety of traditional species, including salmonids, alosines, lamprey, and *potamodromous* species, and have potential for use with nontraditional species as well. Fish lifts and locks often include trap, sorting and transport facilities which may also have an advantage in highly impounded rivers with multiple upstream dams. Once fish are attracted into the fish lift hopper or lock chamber, those facilities can offer the highest passage efficiency of any upstream fish passage structure employed in Atlantic river basins.

Target fish species can be efficiently and quickly lifted from below the dam and either released to the headpond or subsequently trucked to target locations (e.g., for restocking efforts or redistribution of fish to more suitable habitats than the impoundment above the dam) to reduce migration delay.

While they can be effective, fish lifts and locks have some technical and biological challenges. Lifts and locks are not truly volitional passage. Unlike baffled chute or pool and weir designs, fish must wait below the project for the lift to be ready. This wait includes the need for staff to be present to operate the lift. Attraction and retention of fish into the entrance channel before the crowder gates close presents a technical challenge; many species may be reluctant to enter a smooth-walled channel with no obvious exit and remain there for a significant amount of time. Fish that are retained in the entrance channel are prone to delays in between crowding cycles and associated stresses and possible predation. Closure and movement of the crowder gates can also startle fish, with injurious consequences; crowding of too many fish at once can result in overloading of the hopper, with increased mortality.

Fish lifts tend to be somewhat species and size selective. At typical lift facilities, smaller fishes such as eels, small clupeids, and smaller lamprey can potentially swim through retention screens into attraction water structures, and be either trapped there or otherwise have little potential to be lifted before eventually exiting the lift structure. For this reason, most lifts have very poor efficiency for even larger sized eels.

Mechanical fish lifts and locks require intensive maintenance and operational management in comparison to technical and volitional fishways. However their ability to effectively meet management goals often provides important benefits for fish passage and protection and restoration for migratory species.

Design Criteria

Fish lifts and locks may be designed for large spawning runs in major mainstem rivers or for small or infrequent fish runs in smaller tributaries. Large fish locks are uncommon in Atlantic river basins potentially due to higher costs and siting considerations in comparison to fish lifts. Below is a list of basic design criteria used in planning for construction of fish lifts and locks.

- Lift and lock mechanisms should be operated with a minimum of noise, vibration, air entrainment and turbulence, or other stimuli which may startle fish or prevent them from entering.
- Structures in the entrance and crowder channels that introduce strong shadows or require fish to swim under submerged structures should be avoided.
- Design of the lift hopper or lock brail should avoid moving parts, deep corners or sharp edges or protrusions that may trap, pin, or injure fish during the lifting and emptying cycle.
- Lift hoppers should be designed with adequate freeboard or screens to prevent fish from jumping out of the hopper during the lifting process.
- Emptying of the lift hopper or lock brail should be as rapid as possible (e.g., 30 seconds or less) and avoid stranding of fish within the dewatered hopper or brail.
- At hydropower projects, varied turbine operations may significantly influence the ability of upstream migrating fish to find the lift entrance. Evaluation of turbine operations and other flows (spillways, gates) should be carefully considered to optimize fish attraction and passage.
- CFD modeling may be a useful tool to characterize site conditions and facilitate entrance location, especially when combined with observations of fish behavior around dams and powerhouses. Modeling may indicate the need for more than one entrance to address site specific conditions and maximize attraction for passage efficiency.

Chapter 13. Fish Trap and Transport Systems

Application

Fish *trap and transport* systems installed at dams or fishways, also called "trap and haul" or "trap and truck," have been employed for upstream adult fish passage, downstream passage of juveniles, or other fishery management and research activities (Figure 13-1), such as collection of brood stock for hatchery production and for studies that require tagging and telemetry.

Figure 13-1. Example of a trap and haul facility located at the Cataract Falls Project on the Saco River, Maine. *Left and right:* elevator and hopper, holding pool, and black rubber distribution flume/pipes for transfer of fish to a transport tank truck (not pictured).

In some cases trap and transport may be the only viable upstream passage alternative given site characteristics. High head dams with thermal stratification, and/or the presence of multiple dams fully inundating long reaches of rivers pose challenges for effective volitional passage to important upstream spawning habitats. If not designed and operated carefully, use of trap and transport for fish passage may not result in safe, timely, and effective passage because of inherent risks associated with fish handling, limitations on transportable numbers of fish, migration delays in the normal trap and transport operation cycle, maintenance, and funding. Additionally, trap and transport may be considered as a temporary passage phase during construction of permanent upstream passage facilities, or may be used to augment existing passage facilities.

Operational Design

In general, trap, sort, and transport facilities are designed based on target species size and behavior, and the facilities include features to safely route fish into a holding pool. The holding pool may include design features for sorting fish, data collection, safe routing to vehicle transport tanks, and/or return to a volitional upstream passage system, or to the tailwater area. They may also be included in the design of technical/volitional upstream passage systems, fish lifts, and locks or retrofitting existing facilities to allow for target species research and management data collection, tagging, and control of exotic species. The following considerations have proven valuable during the development of facility design and operation plans:

- Overall objectives of the trapping facility.
- Target species and potential handling/transport numbers.
- Non-target species potentially present, and how they may affect trap, sort, and transport capacity and design.
- Operational conditions during trap operation, including flow conditions, debris load and characteristics, and presence of ice.
- Optimal location of the trap facility.
- Planned operational periods consistent with target species migrations.
- Species behavior and characteristics related to needed safe design features.
- Upstream transport locations and practical routes.
- Potential reduction of fish injury, passage delay and stress during trapping, handling, and transport.
- State and federal permit requirements (scientific collection, scientific research, enhancement of the propagation or survival of the species, and incidental take authorization applications).
- A detailed operation and maintenance plan developed in coordination with project staff, stakeholders, and state and federal fishery resource agencies.

Design Components

Trap and transport facilities and operations vary considerably depending on site characteristics, geographic location, and target species. The example shown (Figure 13-1) includes the following components:

- Fish lift with sluice to divert fish to trap holding pool.
- Trap mechanism, including mechanical lift components, diversion gates, etc.
- Trap holding and sorting pool system.
- Distribution flume or pipe for transferring fish to truck tanks.
- Exit channel, flume, or pipe for returning fish to either the headpond or tailwater.

Fish Handling Considerations

Density of fish in transport tanks, water velocity, water and air temperatures, use of low concentration salts (for alosines), duration of transport have all influenced survival of fish during handling. Below are additional considerations for handling based on past experience.

- Nets for sorting, capturing, and transferring fish to tanks or release areas should be minimized or eliminated to the extent possible.
- Use of anesthesia is important for many species and may require compliance with specific criteria for listed endangered species.
- A permit under the ESA is required prior to initiating handling of listed threatened and endangered species.
- An operation plan developed in coordination with fishery resource agencies should include a manual of procedures and reports, forms etc. that the operators follow.
- Personnel involved in handling fish should be experienced or trained in handling methods.

Application

Nature-like fishways were developed as structures for both upstream and downstream passage of fishes and other aquatic organisms beginning in Europe in the late 1970s, although modification of river channels and hydraulic barriers to facilitate passage of fish has probably been practiced since prehistoric times (Katopodis and Rajaratnam 1983). The concept of nature-like fishways is to restore a passage barrier (commonly a dam) to a more natural, river-like configuration by incorporating natural elements such as rocks, boulders, and cobbles to dissipate kinetic energy of water flow, keep velocities within a passable range for most fish and provide resting pools. As such, nature-like fishways constructed of rocks and boulders without reinforcement generally have a low slope below 1:20 (5%), commonly 1:30 (3.3%) to 1:40 (2.5%), both to keep water velocities low and to avoid structural instability that would result from higher water velocities at higher slopes (Aadland 2010). Steeper slopes can be accommodated in nature-like fishways, but these usually require larger boulder structures, reinforcement of substrates with concrete, grouting, sheet pile, or other materials. Structural and hydraulic engineering design guidelines for nature-like fishways at varying slopes, flows, and bed substrate types are described in detail by FAO/DVWK (2002). Restoration of natural river and stream channels and construction of nature-like fish passage in the U.S. is recently described by Aadland (2010). Basic types of nature-like fishways are often referred to as rock ramps or bottom ramps, bypass channels, and fish ramps.

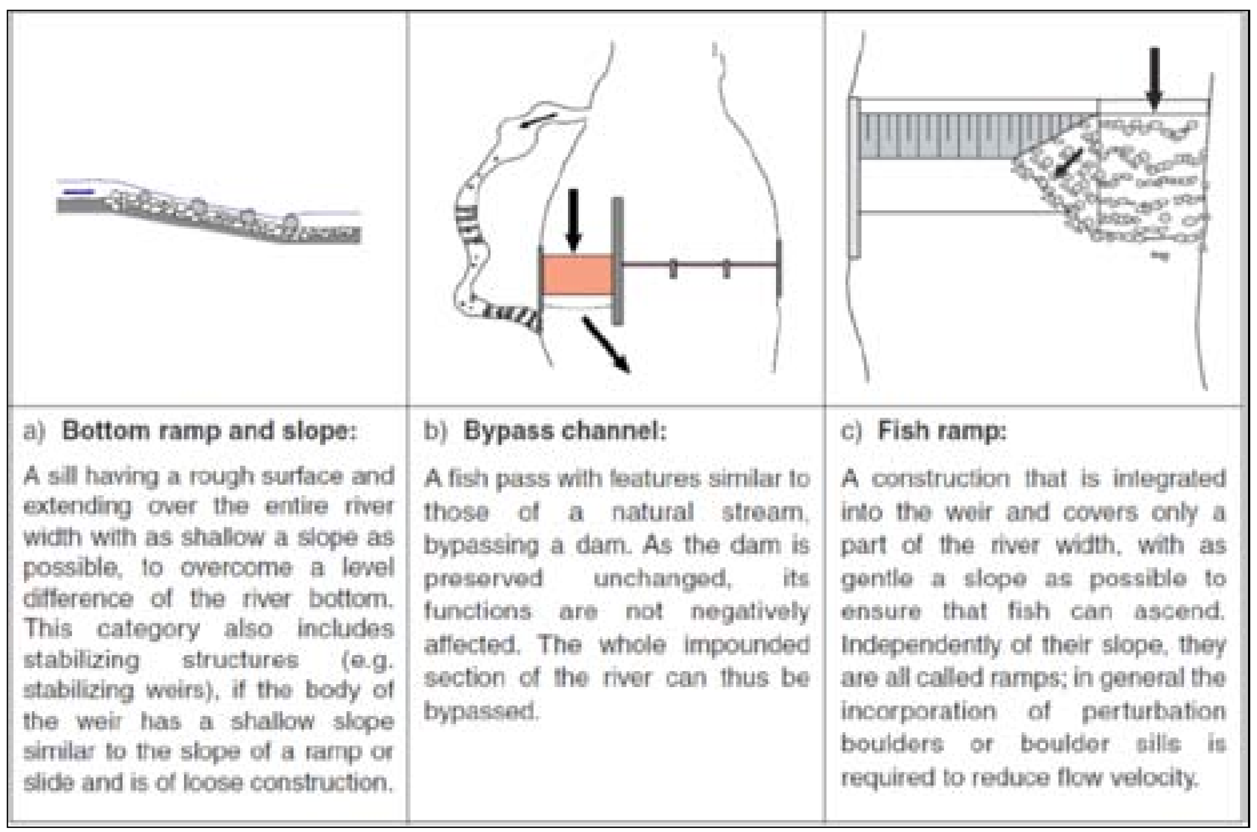


Figure 14-1. Three basic types of nature-like fishways (FAO/DWK 2002).

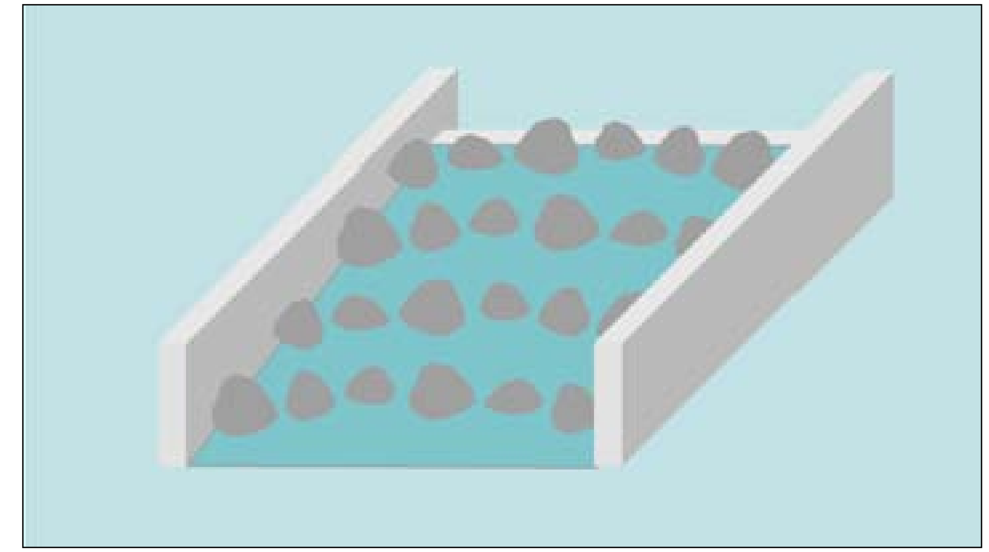


Figure 14-2. Nature-like fishway; bottom ramp/rock ramp design (full channel width). *Below left*: Rock ramp fishway (during construction), and *Below right:* after construction, Sawmill Dam, Acushnet River, Massachusetts.

Figure 14-3. Nature-like fishway; bypass design. *Below*: Heischman's Mill fishway: *Top left:* Entrance *Right:* Transport channel *Bottom left:* Exit control structure *Right:* exit. *Scott Carney, PAFBC*

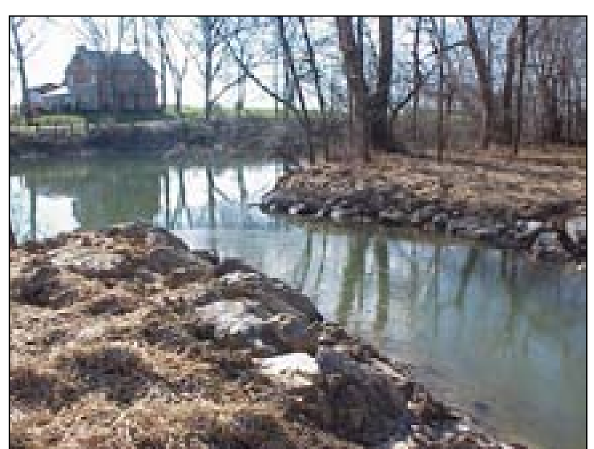
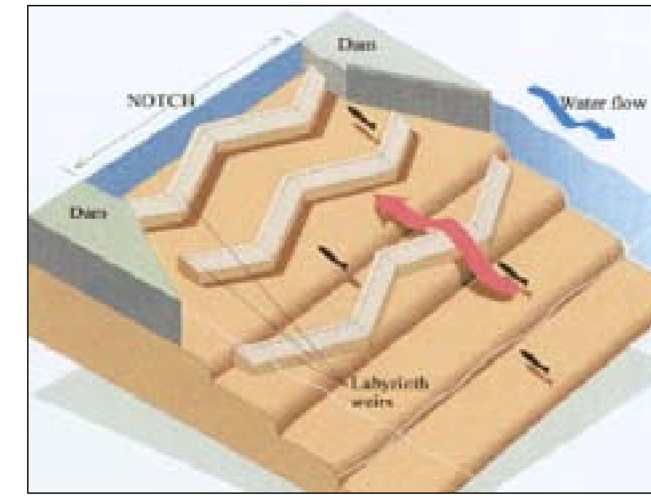


Figure 14-4. Example fish ramp design under construction at Little Falls Dam on the Potomac River. *Right:* Ramp design graphic



Operational Design

An advantage of the nature-like fishway design is that it can be implemented to accommodate the entire flow of a river or stream as part of a dam removal or modification or constructed as a bypass structure if a dam is retained. Variations of the continuum of full versus partial stream width construction form the basis of three general configurations of nature-like fishways (as defined by FAO/DVWK 2002, Figure 14-1)

Bottom Ramp: Bottom ramps are constructed as full-channel width structures; i.e., the entire river flow is directed through the structure (Figure 14-2). They can be constructed over or as part of an existing barrier (e.g., a dam), or to maintain an existing headpond level. In some cases the barrier must be fully or partially removed to ensure structural stability of the ramp, or to accommodate site logistics. Bottom ramps are usually constructed only at dams less than 10 feet in height) and at low slopes to ensure structural stability during high flow events. Internal structure of bottom ramps and fish ramps can be of perturbation boulder or rock weir design (see below). Both bottom ramp and fish ramp structure also need to be carefully designed to avoid jamming or stranding of debris within the ramp structure.

Bypass Channel: Bypass channels are constructed as new auxiliary channels around a barrier (Figure 14-3). As such, they can have variable dimensions and can potentially transport a significant proportion of total river flow (up to 100% in some cases), although design flows are typically less than 25% of river flows. Slope and internal structural design of bypass channels may dictate total allowable flows within the bypass, and in some circumstances bypass flows must be regulated or completely shut off (i.e., for maintenance or high flow events). As with technical fishways, attraction characteristics of bypasses that transport a low percentage of total river flow are important, and fish must be able to transition from a large open river environment to find the smaller channel of the bypass. A bypass design should accommodate target species that require minimum depth and flow conditions. Total length of the bypass channel should also be taken into account. Because of their low slopes, bypass channels on high dams may have considerable length, which may decrease motivation of fish attempting to ascend.

Fish Ramp: Fish ramps are similar in design to bottom ramp structures, but only span a portion of the total channel width (Figure 14-4). Typically they are integrated with existing dam structures. A side retaining wall is often incorporated to maintain flow within the ramp during low flow periods. They can be constructed either downstream of the dam or upstream of the dam, the latter case being more expensive but potentially superior in terms of attraction for fish that may congregate at the base of a dam.

It should be noted that bottom ramp and fish ramp designs are typically constructed to retain an existing impoundment or overcome a hydraulic velocity barrier created by natural conditions (e.g., rock ledge) by simply decreasing the slope downstream of the barrier and adding hydraulic resistance/roughness with natural rock and boulders. Full or partial dam removals may also require addition of bottom/fish ramp designs if post-removal topography still creates physical or velocity barrier conditions.

Structural Design

Functional design of nature-like fishways can take many forms; highly specific standards for their design have not been developed; see FAO/DVWK (2002) for description of forms and relative design standards. Substrate and rock placement within nature-like fishways in most cases takes two general forms: perturbation boulder and rock weir designs.

Perturbation Boulder: Perturbation boulder nature-like fishways have larger rocks set at regular intervals within a bed of smaller rocks or cobbles. Slopes for these designs are usually less than 1:20, yet steeper slopes (up to 1:10) can be accommodated if the larger rocks are embedded within or anchored to a solid base layer (e.g., concrete), or are attached to each other. These steeper slope fishways are usually only applicable to smaller, higher gradient streams and pass a limited number of species (e.g., salmonids). Specific placement of boulders depends on boulder size, slope, and target species; in general, boulders are spaced with adequate zones of passage ("slots") between them. For example, slot width may be twice the body width of the largest species. Likewise, flow depths to accommodate fish size (e.g., two body depths for the largest species to be passed) are typical of perturbation boulder designs. Flow depths vary; functionally, the perturbation boulder fishway acts much like a vertical slot fishway, and increased flow depth does not influence slot velocities significantly.

Rock Weir: Rock weir nature-like fishways are designed to create distinct pools between rows of larger rocks or boulders, which effectively form hydraulic weirs. Flow past the weirs are either through gaps between rocks or over the tops of the rocks themselves, often with a "low" rock incorporated within the row of rocks to create a deeper zone of passage or a low flow passage channel. Slopes of rock weir fishways are usually 1:20 or less, but like a technical pool and weir fishway, overall slope depends on pool length, hydraulic drop per pool, and target species. Drop per pool (and resultant water velocity either over a weir or through a slot) and flow depth over the weir (or slot depth) tend to be the limiting factors for passage, rather than overall slope of the fishway itself. Pool size and depth are important as energy dissipaters of supercritical flow over the weir, and as functioning resting areas for various species. These hydraulic parameters vary according to criteria for the species to be passed.

Shape of the weirs themselves can be variable; straight and curved weirs are common designs, and weirs and pools can also be irregularly shaped or conformed to an existing stream channel. Increasing the length of a weir relative to the channel width increases the effective area, and thus reduces velocities over weirs and through slots; however, excessive open area through weirs lower pool depths. Careful consideration of design flows for both perturbation boulder and rock weir fishways is critical to effective functionality for these designs.

Performance

Nature-like fishways are perceived as having advantages over technical fishway designs in that they create habitat as well as pathways around structures. Designs can provide passage opportunities for a wide group of fishes across a large size range. Some nature-like fishway designs incorporate varying substrates and water depths to create low velocity or resting zones for smaller, more weakly swimming species, as well as deeper flow depths and higher velocities for larger or more strongly swimming species. Few nature-like fishways have been quantitatively evaluated in terms of overall passage performance, and results vary. Initial evaluations of nature-like fishways in Europe via trapping, video recording, or electrofishing have documented varying passage rates of cyprinids (Mader et al. 1998; Santos et al. 2005), mugilids (Santos et al. 2005), salmonids (Eberstaller et al. 1998; Aarestrup et al. 2003; Calles and Greenberg 2005), and percids (Schmutz et al. 1998).

Nature-like fishways have more recently been constructed in Canada and in the U.S. northeast and midwest; unfortunately, few have been quantitatively evaluated for passage. Target species for these projects include alosines and Atlantic salmon as part of removal/restoration programs for small coastal dams and fishway improvements. Franklin et al. (*in prep*) observed high passage rates and short transit times for alewives ascending two nature-like fishway designs in the northeastern U.S., and passage performance of American shad and white sucker (*Catostomus commersonii)* was relatively high in two experimental 1: 20 slope perturbation boulder and rock weir nature-like fishways evaluated in the laboratory (Haro et al. 2008). White and Mefford (2002) documented passage of shovelnose sturgeon (*Scaphirhynchus platorynchus)* in a variable slope experimental open channel with coarse substrate which approached a nature-like design; passage success was dependent on slope and water velocity. Nature-like fishway designs are under consideration in the U.S. southeast for sturgeon, striped bass, American shad, and other alosines.

The long term performance of the nature-like fishway structure stability has not been well studied. However, rock ramp fishways designed to be backwatered under higher flow conditions tend to be more stable structurally (L Wildman, personal communication). The Sennebec Pond rock ramp is a good example of a bottom ramp design that stays inundated much of the year (photos of this project in Appendix II show the site conditions during summer low flow).

Design Criteria

Experience from existing nature-like fishways and technical fishways has been informative in developing preliminary design criteria for select species. Specifications for shad, river herring, and American eel criteria may include a target maximum slope of 5%; channel width of 10 feet, and a minimum depth of 1.6 to 1.8 feet for American shad and river herring and 0.8 feet for American eel (Haro et al. 2008). The maximum effective channel length and full height differential from the entrance to the exit is not well established at this time.

Application

Downstream passage can be necessary for both adult and juvenile fish. Adults of some anadromous species may spawn multiple times if they survive the outmigration from their spawning areas, and adult American eels must successfully pass downstream to get to their spawning grounds in the Sargasso Sea. Juveniles of all anadromous fish have to get to the ocean to mature and return to their natal stream for spawning. Without effective downstream passage systems at hydropower plants, fish are subject to possible injury and mortality from turbine passage or from passing over spillways. In addition, delay at dams can result in predation from birds, fish, or mammals and adversely affect physiological changes of species, e.g., *smoltification.* Fish protection and passage is also necessary at water diversions, whether the diversion is for irrigation, cooling water or potable water. Downstream passage measures provide protection for all life stages of diadromous and resident fish species. During development and design of downstream passage and protection systems, an analysis of site conditions and species behavior at the project site can provide information considered necessary to identify the best practical and protective design criteria. Water diversions include intake systems for industrial process water, municipal water supplies, and agricultural irrigation. Diversions are essentially dead-end pipes or canals that may entrain all life stages of fish and in many cases may result in significant mortality.

Ideally, the target for safe, timely, and effective downstream passage and entrainment protection is 100% survival for all life stages target species past the project. Project-specific objectives will reflect the details of restoration goals, site conditions, and project operation limits.

Operational Design

Effective downstream fish passage protection systems prevent fish entrainment and impingement at hydropower turbine intakes, and many types of water diversions. Downstream fish protection and passage facilities consist of two primary components: fish protection barriers and bypass systems. Fish protection barriers block fish passage into, through, or over hazardous routes, guiding the migrants to the bypass system, or conduit, which conveys the fish around the impediment and safely back to the river. A properly designed fish conduit can provide safe and effective passage past the dam or other obstruction. NMFS has often sought entrance designs that did not elicit a behavioral avoidance response (e.g., streamlines and uniformly accelerating entrance flow) given that fish react to the hydraulic change of accelerating or decelerating water flow, and some swim upstream to a point of uniform flow. This reaction can keep the fish from entering the conduit until the fish weakens. The bypass would have either a surface entrance for surface oriented species, such as alosines and salmon, or a bottom entrance for those species, such as sturgeon and eels, that migrate along the bottom. A surface entrance would have a downward opening gate leading to a flume or pipe. In some cases if the barrier is on the existing river embankment, and flow parallel to the barrier is adequate, there is no need for a bypass, as the fish are still in the river and can continue downstream.

Structural Design and Criteria

Fish protection barriers may be classified as behavioral or physical. Behavioral barriers are dependent on the behavior of the fish to be effective. The desired behavior results from changes in hydraulic conditions encountered by the fish as they approach the barrier, or startling effects of lighting or sound generation devices. Behavioral barriers include angled bar racks, louvers, guide walls, curtain walls, barrier nets, lighting, sound, and other devices.

Physical barriers are intended to prevent fish from entering an area by their presence alone. These barriers have small openings through which the fish are less likely to pass, minimizing the movement of fish into turbine intakes and water withdrawals. Many fish normally face upstream as they out-migrate and swim at a speed less than the water velocity, which results in downstream movement. When they approach a screen, they continue to face upstream, but move along the face of the screen or bar rack toward the bypass entrance. The normal velocity, which is the velocity through the barrier, is critical. The velocity must be low enough that the fish will not be impinged on the barrier. The velocity criteria depend on behavioral characteristics of the species being passed. Thus the barrier design depends on fish size and swimming ability, overall barrier dimensions, porosity, clear spacing of bars, and the quantity of water that needs to be passed. Physical barriers include several designs: bar racks, fixed vertical plates, vertical traveling screens, modular inclined screens, rotary drum screens, Eicher screens, and simple end-of-pipe (pump) intake screens. Basic bar rack and louver designs are shown in Figure 15-1.

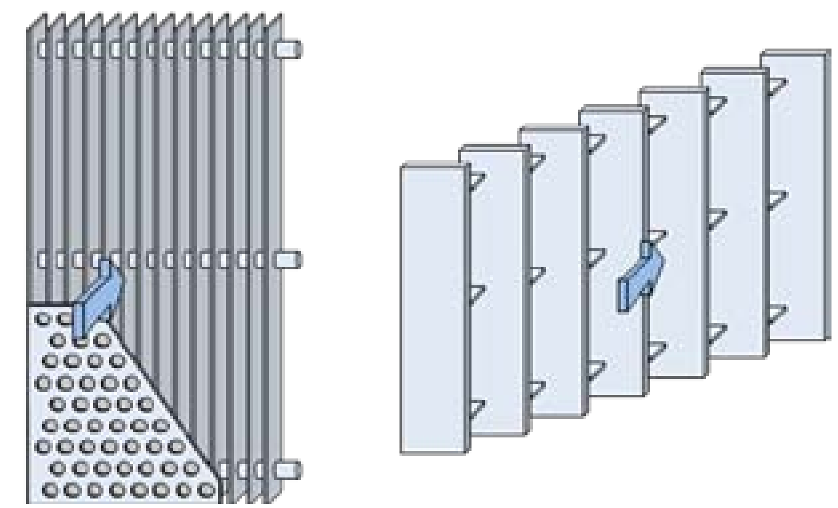


Figure 15-1. Physical barrier bar racks and behavioral design louvers. *Left:* vertical bar rack, shown with partial perforated sheet metal overlay. Arrow indicates direction of approach flow. *Right:* louver array, with flats of bars oriented perpendicular to flow.

Louvers: Louvers consist of an array of vertical bars mounted in a rack. The rack crosses the forebay or canal at a shallow angle, typically 15 degrees. The bars are perpendicular to direction of flow and spacing between them is typically 1 to 4 inches dependent on target species and age class. Fish are guided by the hydraulic condition associated with the abrupt change in flow direction through the louvers, which they discern several inches upstream of the louvers. While avoiding this hydraulic action they move downstream along the face of the array toward the bypass entrance. Louvers have not been universally accepted, because different sizes and species of fish react differently to the flow change and there can be significant entrainment of small or weak swimming fish. An example of the louver system at Holyoke Dam on the Connecticut River is shown in Figure 15-2.

Curtain Walls: Curtain or guide walls are angled solid barriers in the forebay that extend from the surface to a depth which is related to and dependent on the depth of the forebay. The angle of the wall guides fish to a surface bypass opening. Curtain walls are only useful for surface oriented species, and they must be deep enough to prevent fish from sounding and passing under the lower edge of the wall. They are not effective for sturgeon or out migrating adult eels, as these fish are bottom oriented and pass under the curtain wall, ending up at the turbine intakes. An example diagram of a guide wall downstream passage bypass system on the Connecticut River at the Bellows Dam is shown in Figure 15-3.

Bar Racks and Screens: Bar racks and screens are commonly used for physical and/or behavioral barriers and these can be either angled or perpendicular to flow (Figures 15-4 and 15-5). They are similar in construction to trash racks with vertical or inclined steel flat bar members. Depending on flow requirements, bar racks can replace trash racks. Typical clear spacing of the bars for various life stages of Atlantic salmon range from 0.5 to 1 inches between the bars, though 1 inch are more common[2]. Bar rack spacing currently under consideration for silver eel is a maximum of three-quarter- inch[3]. Square mesh or perforated plate ("punch plate") attached to trash racks is used as a physical barrier for anadromous and catadromous species. Depending on the species of concern these overlays can be either full or partial depth. Wedge wire inclined plane screens are used as barriers for dewatering in sorting facilities. Mesh and wedge wire screens are normally stainless steel, and plastic has been proposed for some experimental screening applications.

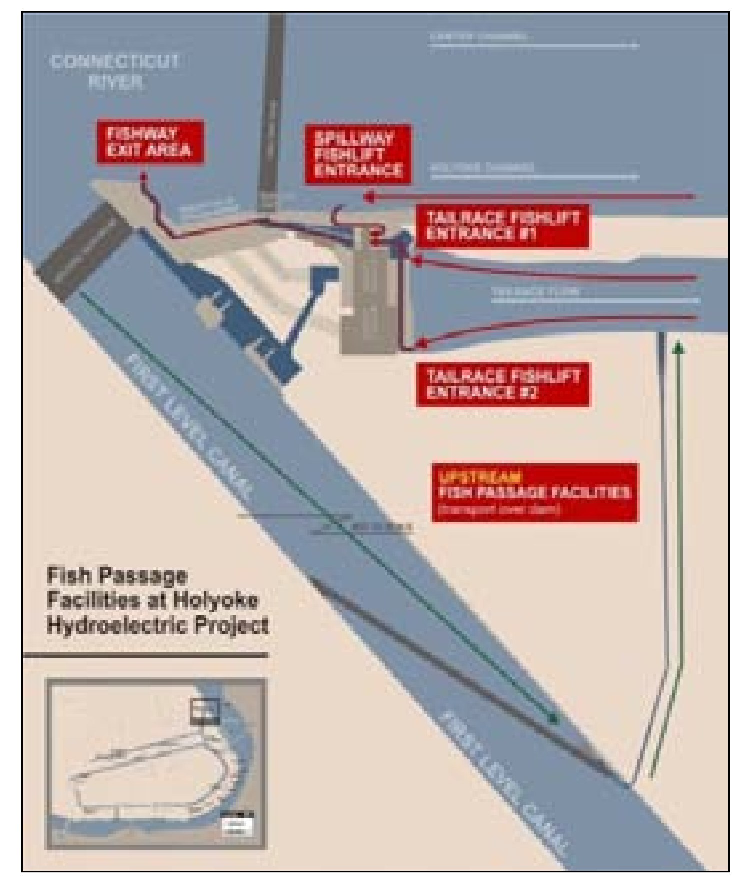
Bypass Systems: Bypass systems are typically surface or bottom oriented. Surface bypass systems are typically used for out-migrating adult and juvenile salmonids and alosines. This system may also be utilized by American eel. Bottom bypass systems typically target adult American eel. Both systems must have a means of closing the entrance. Valves should not be used because they can result in injury to fish, particularly juveniles. The corners of the opening need to be rounded and the radius has to be large enough that fish don't adversely react to flow acceleration (e.g., >24 inches diameter). The inside should be smooth, and the minimum bend radius should be 10 feet. The outfall of the bypass conduit, be it flume or pipe, should be elevated above the water surface downstream of the obstruction being passed, and away from predator holding areas. In addition, a plunge pool at the point of impact of the outfall from the bypass will help reduce injury and mortality. Bypass outfalls should be located where the receiving water is of sufficient depth (depending on the impact velocity and quantity of bypass flow) to ensure that fish injuries are avoided at all river and bypass flows. The bypass flow must not impact the river bottom or other physical features at any stage of river flow. In areas of heavy bird predation, water spray or horizontal wire barriers may be necessary.

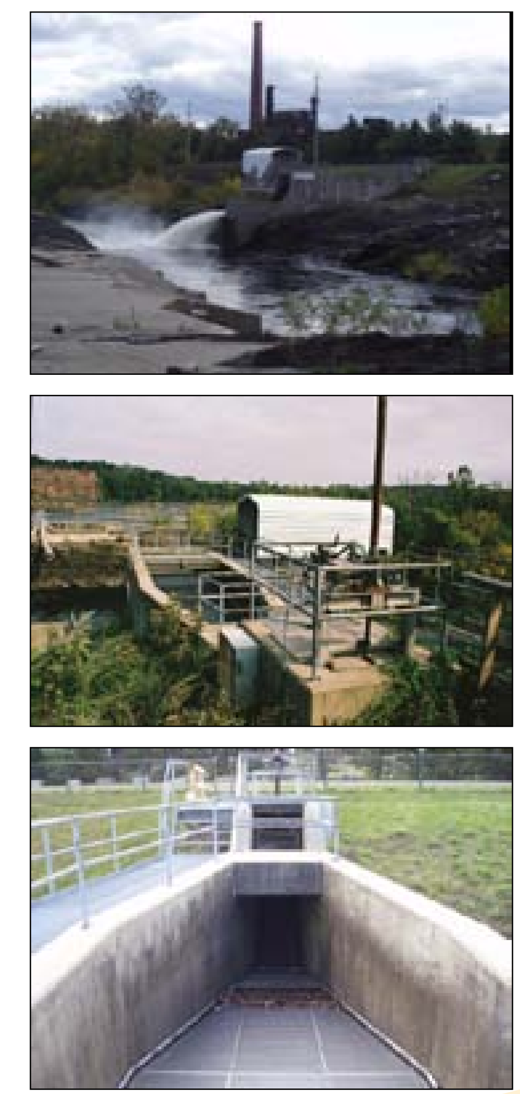
Spillway Passage: Most hydropower dams have spillways to allow for passage of water exceeding the flow capacity of the power plant turbines (Figure 15-6). Spillway passage for downstream migrating fish generally provides higher survival than bypasses and turbines. Benefits of spillway passage include reduction in delays at the forebay and tailrace, and often reduced predation. Problems with spill passage include generation of high levels of dissolved gases, danger of high velocity when fish pass under spill gates, inadequate plunge pool depth causing injury to fish, and loss of significant water flow volume for power generation profits. The use of directed, concentrated spill through gates or other means at the spillway is an effective method of downstream passage. The amount and timing of spill (in cfs) should be determined in coordination with fishery resource agencies.

2 One inch bar racks are utilized at a number of hydropower facilities in the northeast, including the Weldon, Orono, Stillwater and Milford Projects, Maine; Cabot Station, Massachusetts; and Wadams Project, New York.

3 Criteria for bar racks to act as a physical barrier for silver eel remain in development. The size criteria here are based on silver eel biometrics.

Figure 15-2. Example louver system for downstream passage at Holyoke Dam, Connecticut River, Massachusetts. *Above:* Constructed louver in the first level canal *Below:* Diagram showing louver and bypass location, shown by arrows, in the first level canal, and photo of the bypass outfall. The bypass outfall also includes a downstream evaluation unit with an inclined screen collection system.





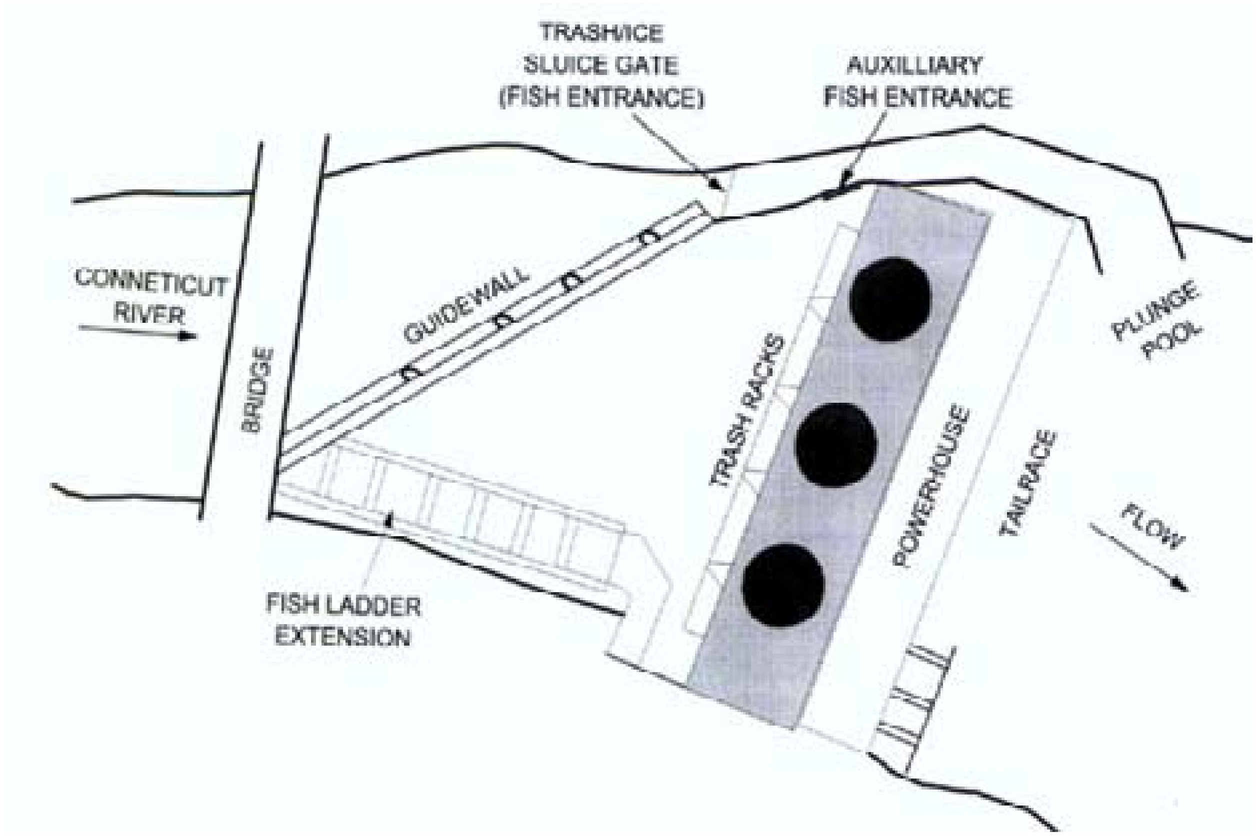


Figure 15-3. Downstream passage system at Bellows Falls Dam, Connecticut River (Odeh and Orvis 1998). *Above:* Diagram showing guide wall, diversion channel, and plunge pool. *Below left:* Upstream view of the guide wall and fish bypass entrance. *Below right:* Bypass fish discharge and plunge pool.

Figure 15-4. *Above:* Example bar rack and entrance to the bypass conduit. Pine Valley Project, Souhegan River, New Hampshire.

Figure 15-5. *Above right:* Example fish bypass entrance with bar rack, Columbia Project, Broad River, South Carolina. Bar rack prevents fish entrainment at 7 turbines; bypass is located at an extra turbine bay with outfall to the tailwater. *Bottom Left:* Bypass entrance design with surface entrance gate, and bottom gate for bottom-oriented eels and sturgeon. Note: Debris accumulation requires frequent cleaning for effective fish passage.

Turbine Shutdown: The complexity of some sites presents a challenge to guiding fish to a bypass facility. Where multiple tested alternatives fail to pass fish in a safe, timely, and effective manner, turbine shutdowns should be considered. For American eel, which is not surface oriented and frequently occupies a variety of depths in hydroelectric dam forebays while presumably searching for a safe route of downstream passage (Brown 2005; Brown et al. 2009), modification of project operations (e.g., unit flow reductions or shut-downs) has the potential for reducing turbine mortality (Haro et al. 2003). However, effects of potential increased spill mortality of downstream migrant eels as a result of such project operation modifications are unknown (Euston et al. 1997). Shutdowns for the protection of American eel[4] and federally endangered Atlantic salmon[5] have been incorporated at hydropower projects on major rivers in Maine. The timing and duration of turbine shutdown should be developed in coordination with the resource agencies.

Turbine Passage/Mortality: In the absence of properly designed fish screening and bypass systems, all life stages of fish migrating downstream risk entrainment through the turbine intakes. The most common turbines at Atlantic river basin dams include Francis and Kaplan type (Franke et al. 1997). The Francis type generally results in higher fish mortality rates (Direct: 20% to 30%), and Kaplan turbines are generally lower to moderate in comparison (direct: 5% to 10%). Indirect mortality involves injury and delayed mortality, dependent upon environmental conditions, and increased probability of predation. Mortality rates are highly variable dependent upon fish species behavior, adult size, and life stage; hydraulic head (height of the dam), thermal stratification in the reservoir, and many other factors. Adult fish are subject to significantly higher mortality rates due to size and body form characteristics. Generally, the larger the size and length of fish, the more impact turbine runners may have on injury and mortality. In addition to direct mortality, fish passing through turbines may be adversely affected by pressure changes to the entrained fish, cavitation caused by localized pressure differences on the trailing edges of runner blades, and shearing at the boundaries of water layers that are moving in different directions. Figure 15-7 shows an example hydro facility and its components, linked to mortality factors.

4 Of note is the FERC Order for subsequent license, dated Oct 2, 2003 for the S.D. Warren Projects (Project Nos. 2897, 2931, 2932, 2941, 2942) on the Presumpscot River. Articles of the license require seasonal nightly shutdowns for the protection of downstream migrating silver eels.

5 NMFS December 23, 2009 Endangered Species Act Biological Opinion for the Surrender of Licenses for the Veazie, Great Works and Howland Projects, Nos. 2403, 2312, 2721. Protective measures in Biological Opinion include season shutdowns of the turbines for the protection of out migrating smolts.

Figure 15-6. *Above:* Diversion dam downstream spillway passage at the Columbia Project minimum flow gate, Broad River, South Carolina, vertical slot upstream pass fishway. *Paul Cyr, Kleinschmidt Associates Below:* Spillway passage at Holyoke Dam, Connecticut River, Massachusetts.
Al Blott, NMFS

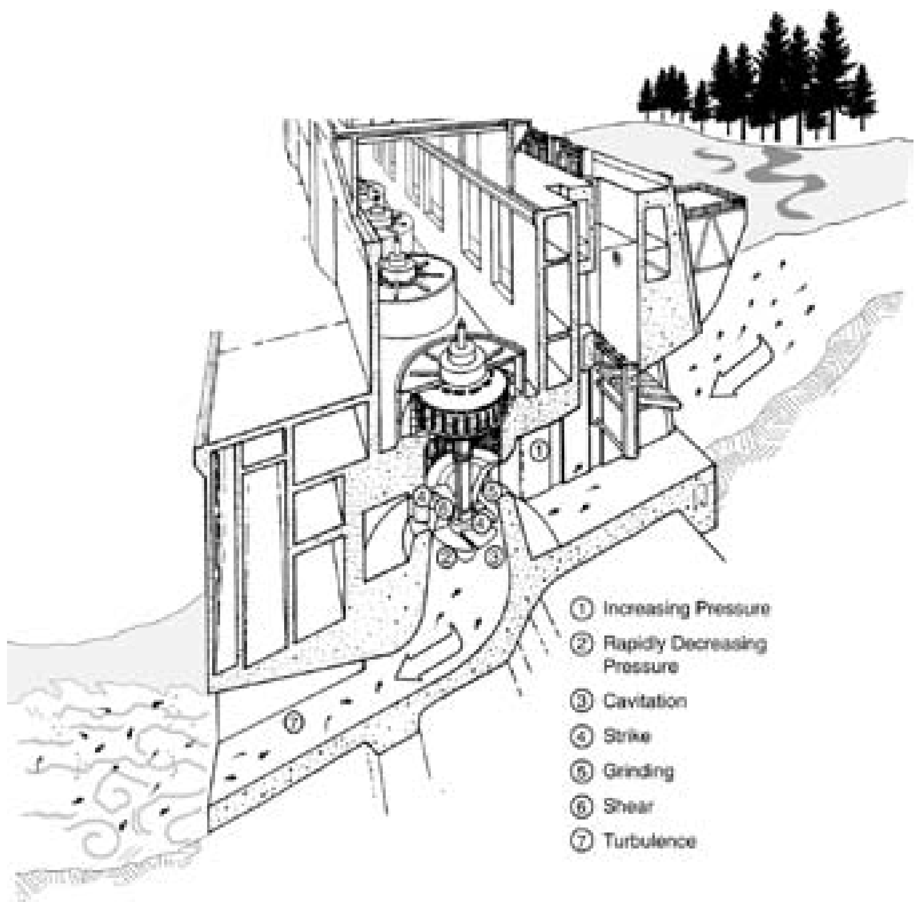
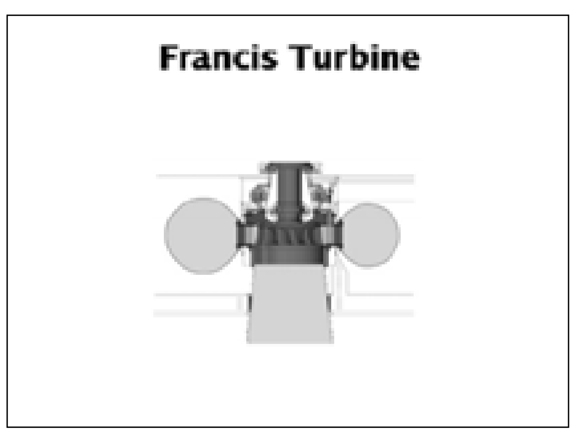
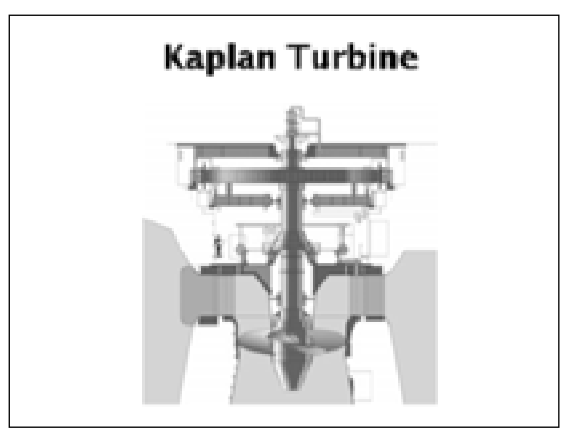


Figure 15-7. Example hydropower dam components and turbine mortality factors, Kaplan turbine type. *Below:* Example Francis and Kaplan turbine designs.





Fish Protection at Water Diversions and Intakes

While the previous sections focused on hydropower facilities, physical barriers in rivers and streams that divert water for public consumption or agriculture also may present incomplete or complete passage barriers for fish. In many cases, use of water for public consumption or agriculture requires fine mesh screening to exclude debris from pumps or other equipment. Often water bodies used as sources contain fish of very small sizes that should be completely prevented from entering a water intake to ensure adequate protection. Similarly, cooling water withdrawals for thermal-electric power generation projects pose high risks of lethal entrainment or impingement to downstream migrant fishes, particularly for juvenile, larval, egg and post-larval early life stages. Protection of potentially entrained fishes at power plant intakes usually falls under jurisdiction of the Clean Water Act §316(b), which requires fine-mesh screening devices and criteria for screen velocity, or the ESA if a listed species is present in the action area. Power plant cooling water intakes often include measures to reduce impingement, such as rotating drum screens or traveling screens, which are complex structures of varying design, and also behavioral barriers, such as sound and light. See Taft (2000) for a review of these devices and their applications.

Withdrawals of water for consumptive use and agriculture can be significant, requiring large, complex facilities that utilize numerous technologies to exclude and protect fish. Positive barrier screens have long been considered the best technique to prevent entrainment of fish into a diversion and can be expensive and difficult to maintain (USBR 2006). Behavior guidance technologies have not generally been effective at water intake structures, in comparison with positive barrier screening systems. See USBR (2006) for a review of exclusion technologies for water withdrawal structures and their effectiveness.

Rotating Drum Screens: Drum screens are cylindrical frames covered with woven wire screen material and placed at an angle to river flow with the cylindrical axis horizontal (Figure 15-8). The facility may be a single cylinder screen at narrow diversion sites, or a series of cylinders placed in line end-to-end. Drum screens rotate slowly with the entrance surface rotating upward, and the downstream surface rotating downward. The drum is placed at an angle to the inflow to create a sweeping velocity so that fish encountering the screen face are guided to a bypass facility at the end of the drum.

Traveling Screens: These facilities are complex mechanical designs with the often vertically oriented flexible screen moving continuously or intermittently to keep debris from collecting on the screen face. The system is designed to remove fish and fingerlings, which are unable to escape from in front of the screen, and to safely transport and return them to the source water downstream of the screen intake.

Fish survival rates at traveling screens are maximized when the screen is coupled with a means for the fish to escape the intake current. This can be accomplished by sizing the screens to limit approach velocity and by providing escape/bypass passageways for fish. Fish and debris removal features include separate dedicated low pressure water spray headers and troughs for fish and debris. The spray devices are specifically designed to preclude injury of fish. A screen drive mechanism is placed on a platform above the high water surface, with a secondary rotating drum and spindle at the submerged screen bottom. Vertical traveling screens are commonly used at industrial process or cooling water intakes, with relatively small to moderate size and low velocity intake flows. At higher flow irrigation facilities, the screens are configured so that the screen face is parallel to or at a shallow angle to the flow, to provide a sweeping flow for guiding fish to a bypass facility, returning them to the river downstream (Figure 15-9).

Flat Plate Screens: Example flat plate screens with vertical "V" configurations (Figure 15-10) are used for small to large irrigation or water supply diversions where total fish exclusion is needed, as in California, Washington, and Oregon where salmonids are listed as endangered or threatened under the ESA.

Inclined Screen Designs: There are two general design concepts for inclined screens (Figures 15-11 and 15-12). The first design includes a fixed screen angled in line with the intake flow, completely submerged, with an upward slope. The sweeping flow velocity moves fish up the screen face, progressively shallower, then over to a bypass facility at the downstream end. The majority of the water flow passes through the screen, and on to the water intake canal or pipe delivery system. Inclined screens may be fixed or designed with a moveable frame allowing adjustment of the screen face to match varying water surface elevations. Similar inclined screens are also employed for fish bypass evaluation facilities.

The second inclined screen design is developed for intake facilities located on a stream or river bank beside the channel. The inclined screen is placed parallel to stream flow to provide a sweeping velocity along the screen face to guide fish life stages downstream past the facility. A compressed air or "air-burst" piping system may be needed to aid in debris removal. Approach velocity and sweeping velocity criteria are used to develop screen designs to ensure adequate protection of migratory and riverine fishes. The screen face is generally designed also to provide adequate intake volume and fish protection during low or high flow conditions. Streambank inclined screen facilities may not need fish bypass facilities; however, when located in canals, designs must include configurations to provide sweeping flow to a bypass facility.

Cylindrical Intake Screens: Various designs for cylindrical intake screens are developed for gravity or pumped water diversion pipes and conduits to supply water for irrigation, small industrial process water, and small hydropower plants (Figure 15-13). These cylindrical intakes can be either fixed or track-mounted retrievable designs that can be raised up out of the water when flow is not needed. Flow rates are typically less than 100 cfs for process water intakes and hydropower, and 1 to 5 cfs for small irrigation pump intakes. These screens are generally fully submerged in ponds, canals, streams, or river channels. The designs typically provide full protection for all fish life stages, and bypasses are not necessary.

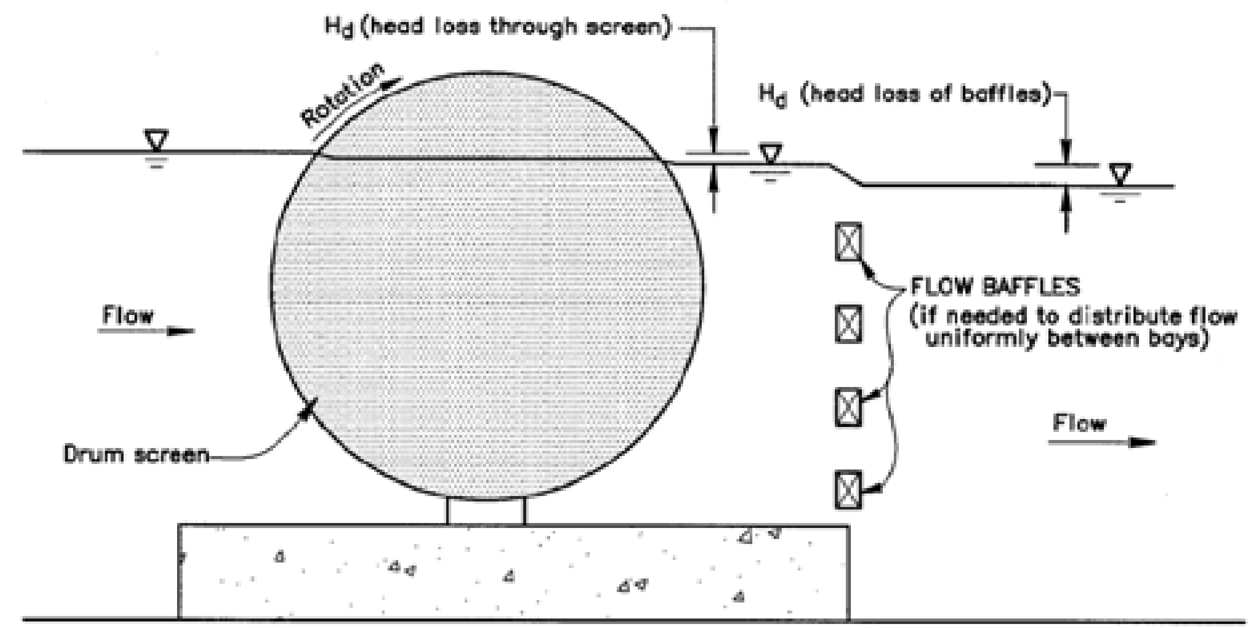


Figure 15-8. Example diagram of a typical section of a drum screen. (Pearce and Lee 1991). *Below:* Drum screens at Roza Diversion Dam, Washington. *USBR 2006*

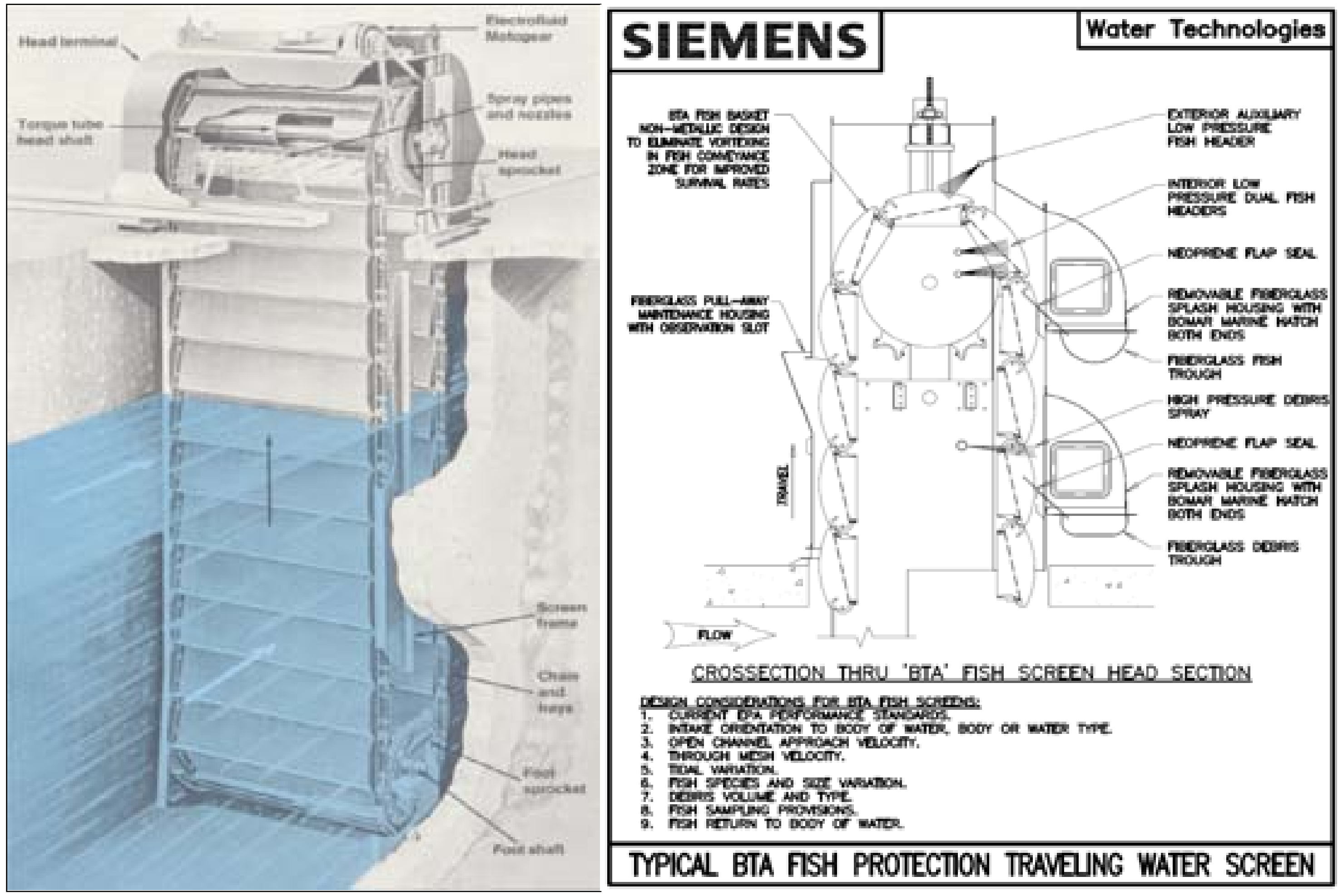


Figure 15-9. Example diagram of power plant intake traveling screen system. *Top left:* conceptual drawing *Right:* engineering diagram *Bottom:* Photo of screen drive system. *Photos and diagrams courtesy of Steve Thomas, Siemens Corporation.*

Figure 15-10. Flat plate screen "V" configuration with a terminal fish bypass, Red Bluff, California. *USBR 2006.*

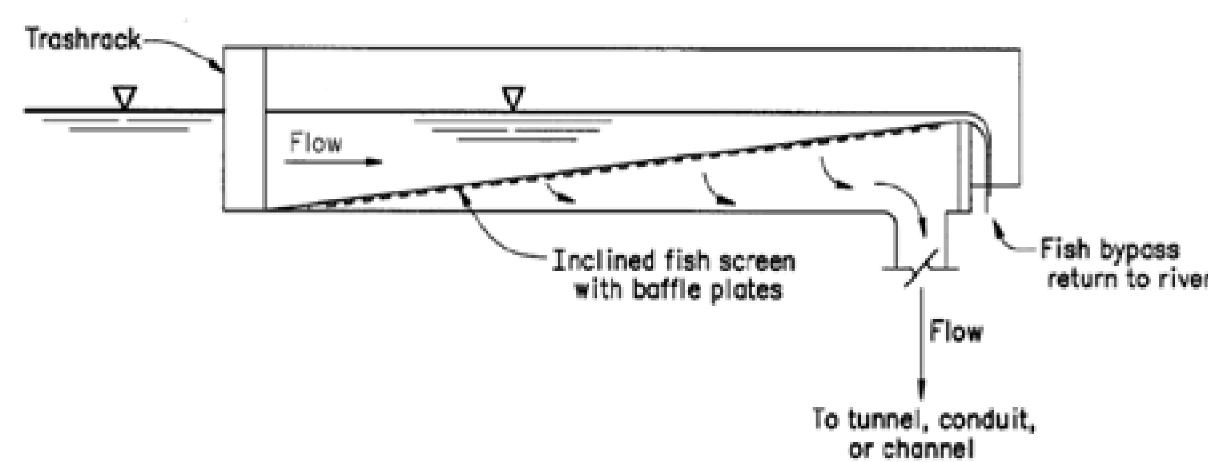


Figure 15-11. Inclined "flat plate" screen diagram and example with fish bypass, Hood River, Oregon. *USBR 2006*

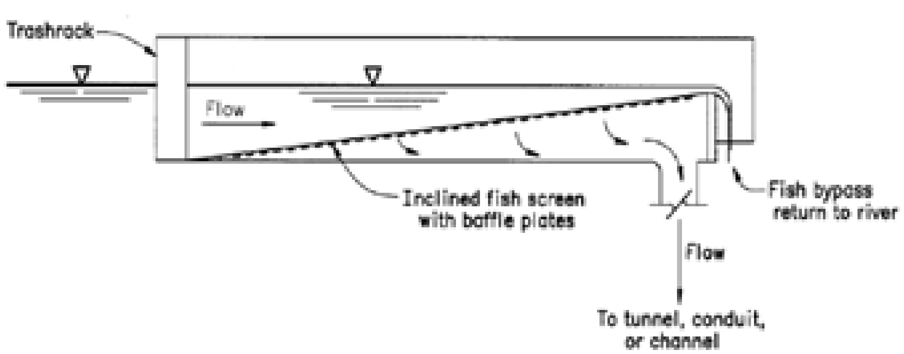
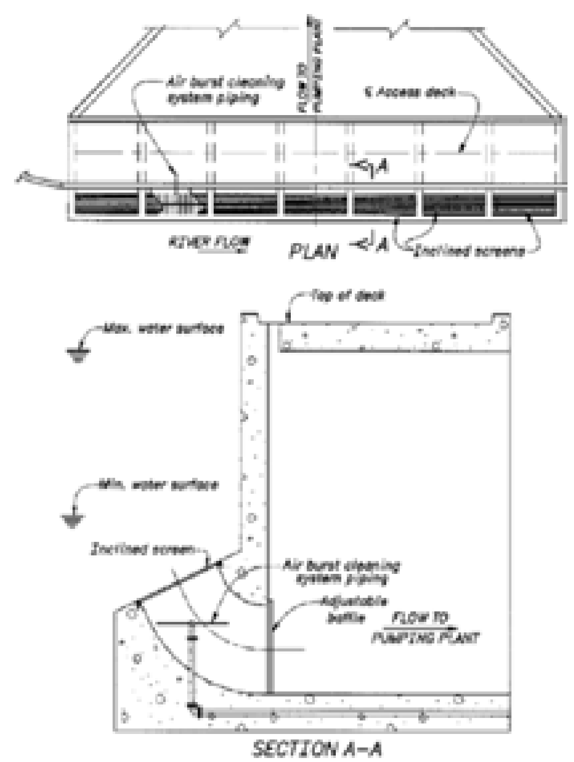


Figure 15-12. Inclined screen, riverbank design with air burst cleaning system for debris. River flow parallel to screen aids in fish protection. Upper plan view, lower sectional view. *USBR 2006*



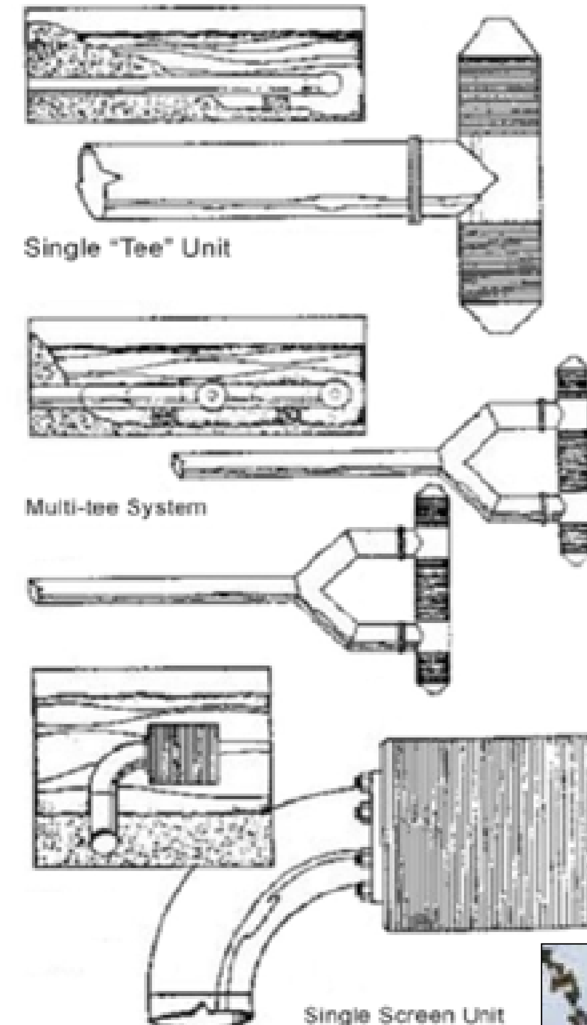


Figure 15-13. Fixed cylindrical screen design (Johnson screens). *USBR 2006*
Below: Example track-mounted rotating cylindrical screen with brush cleaner.

Chapter 16. Small Barrier Passage

Introduction

Millions of small barriers including abandoned historical mill dams, agricultural irrigation ponds, municipal water intake ponds and diversion dams, recreational and private lakes and ponds, small road crossings with culverts not designed for fish passage, etc., are in place throughout smaller tributaries and headwater streams in all river basins in North America (Graf 2002). Obtaining fish passage is often of ecological importance for riverine aquatic species. Small fishways, re-designed roadway culverts, dam notching or removal of abandoned or obsolete dams are practical and important measures for restoring populations of aquatic species and meeting fishery management goals.

Small Impoundments and Diversion Dams

Obtaining fish passage at smaller, non-hydroelectric barriers including stream crossings, small impoundments, water diversion dams or weirs, etc. often requires different approaches than basic installation of fishways or traditional downstream passage structures. Fish passage at smaller obsolete barriers has often been best dealt with by physical removal of the barrier. Removal can be more cost-effective than construction of associated passage structure and long-term maintenance of the barrier. Alternatively, if the hydraulic head of a small dam or other barrier is not significantly high, effective passage for some species may be possible by notching of the dam (see Chapter 5, *Dam Notching and Removal*), or construction of a nature-like bottom ramp or fish ramp (see Chapter 14, *Nature-Like Fishway Design*).

When removal of small barriers is not feasible, notched, or modified as a ramp, other modifications may be applied to enhance passage without altering hydrography or functional and structural integrity of the barrier. These modifications are dependent on the type of small barrier and its intended function. Small fishways, like the steeppass shown in Figure 16-1 are often practical for fish passage for ocean-river migratory fish as well as riverine fish.

Stream Crossings and Culverts

Stream crossing structures such as culverts are usually constructed at smaller streams (Figure 16-1). Culverts are rigid, fixed structures which must pass varying flows from a dynamic stream environment. As the natural stream channel changes, culverts often are not able to fully accommodate those changes and hydraulic and physical barriers to passage are created. Culverts can reduce or block passage for adult or juvenile fish and other aquatic species (discussed below), unless special design features are included during construction. Although the amount of habitat affected by an individual culvert may seem small, the cumulative impact of multiple roadway culverts within a watershed can be substantial.

Figure 16-1. Example “perched” culvert barriers and a passage design at right. *Below:* Example small dam with steeppass passage facility, also frequently useable for perched culverts.

Culvert and other stream crossing designs are diverse, depending on their scale and functionality. Hydraulics within these structures are usually optimized to maximize flow during high flow events, which create velocity and/or turbulence barriers, even under low flow conditions. In addition to flow, the severity of these hydraulic barriers is dependent on culvert length, slope, size, bottom area, and substrate type. Changes in the hydrography or poor construction methods may result in the outlet of culverts becoming *perched*, and therefore impassable to species that do not jump. Longer culverts are often dark inside, which may create a "visual" barrier for fish species reluctant to pass environments with minimal lighting.

Alteration of culvert design, slope, size, and substrate type, as well as "daylighting" to reduce darkened zones may alleviate potential barrier problems. A description of these alterations and engineering criteria is beyond the scope of this document; for a comprehensive review and design tools, see the FishXing (Fish Crossing) website: http://www.stream.fs.fed.us/fishxing/

States have also developed standards for culvert design and replacement with specific design standards for fish passage (Maine DOT 2007; also see http://www.streamcontinuity.org/online_docs.htm for similar guidelines for Connecticut, New Hampshire, Vermont, and Massachusetts). Federal design standards for provision of passage through culverts also exist (FHA 2007), however, and state and federal design and operation standards may vary widely.

Goals and Process

Adequate hydraulic and biological functionality of fish passage structures is an important component to successful restoration of diadromous fish populations. Hydraulic and biological evaluation and monitoring of passage structures in the field on a site-by-site basis has provided the most reliable method of assessing passage performance.

It is important to note that evaluation and monitoring can be conducted over a variety of scales; i.e., through a specific structure, through an entire project (with multiple routes of passage), within dammed and undammed reaches, or throughout an entire watershed, or multiple watersheds, depending on objectives for the study.

Biological evaluation and monitoring involve assessment of functionality of the structure in passing target species, and may be conducted for both upstream and downstream passage structures. It is important to distinguish between biological ***evaluation*** of passage structures and biological ***monitoring***. Evaluation usually involves numeric quantification of passage performance in relative terms; e.g., percentage of fish passed over a given unit of time or throughout a migratory season. Typically, biological evaluation is performed soon after a structure is constructed for a limited number of seasons to assess performance in meeting passage goals. Monitoring can involve absolute numeric counts of fish passing the structures (i.e., individuals per day or per season), and makes no inferences about level of passage performance. Biological monitoring may be conducted over a structure's lifetime to quantify absolute numbers of fish passed, generally to assess population size passed upstream or downstream. Monitoring data can under some circumstances potentially be used to infer quantitative passage (i.e., as an evaluation). For example, comparing fish counts at successive dams can yield minimum percent passage estimates. It is important, that monitoring data are accurate, and such an analysis should not be viewed as a substitute for a more quantitative traditional biological evaluation. A comparison of specific components of evaluation and monitoring techniques (described in more detail below) and their associated cost and level of technical difficulty is given in Table 3.

Unfortunately, only a small number of passage structures have been evaluated (FERC 2004), and many past evaluations are only qualitative in nature (i.e., compliance with design specifications, simple observations of some species passing a structure). Because of the paucity of evaluation data, many structures have unknown performance. Site-specific characteristics (e.g., structure siting, local flow fields, project design) have a profound effect on overall structure performance, such that the same fishway design can perform well at one site, but not at another. There are no standards for evaluation study design, protocol, and data analysis. Detailed information on current approaches to and techniques of upstream and downstream passage evaluation and monitoring can be found in Almeida et al. (2007), FAO/DVWK (2002), DWA (2006), Castro-Santos et al. (2009), and Travade and Larinier (2002).

Developing Upstream and Downstream Passage Effectiveness Evaluation Study Plans

Study designs for performance evaluations of both new and old structures have often been based on specific objectives, questions, and data needs in order to provide optimal results. Target species and life stages to be passed should be identified, and any non-target species that may become target species in the future should be considered. Depending on restoration goals, acceptable performance of a structure may vary from the simple ability to pass target species to more specific performance benchmarks; i.e., minimum acceptable percent passage, minimum delay times, and quantification of effects of passage on stress and reproductive potential. The nature of the data to be obtained should be determined prior to discussion of experimental design. In the case of new structures, a comprehensive evaluation protocol should be an integral part of the project design. At some sites, both upstream and downstream passage may be required to operate simultaneously.

Even when dedicated downstream passage is available, evaluation of potential use of upstream passage by downstream migrants may be part of a comprehensive design to maximize overall passage efficiency and effectiveness. Outside expert peer review of study designs may be necessary where uncertainties in study protocol, data return and quality, or statistical rigor exist. Multi-year studies may be needed to account for year-to-year environmental variability that can influence the results of an evaluation study for a particular season.

Hydraulic and Operational Evaluation Methods

Measurement of hydraulic and operational features of the passage structure are commonly made soon after construction is completed, and prior to fishway operation for passing fish (Figure 17-1). This "shake down" period ensures hydraulics meet design specifications and/or that modifications to flow control structures or physical features can be adopted if necessary before functional operation of the passage structure begins. Evaluation metrics vary from structure to structure, but usually include operational flows, water levels, and velocities (point, 2D profile, or 3D flow field as applicable). Documentation of operational hydraulic or flow field characteristics (e.g., flow separation, plunging/streaming flows, air entrainment, turbulence) can also be made via photography or video recording. Automated or computer control of flow structures are also tested under varying river flow or project operation conditions to verify functionality under varying head or flow. Assessments of fouling, debris loading, etc., are also typical to establish adequate maintenance schedules. Hydraulic and operational evaluation criteria to consider include:

- Model and design verification.
- Benchmark hydraulics, monumenting, and photographs.
- Measurements at low and design flows.
- Long-term measurements (e.g., settling, structure movement, erosion).

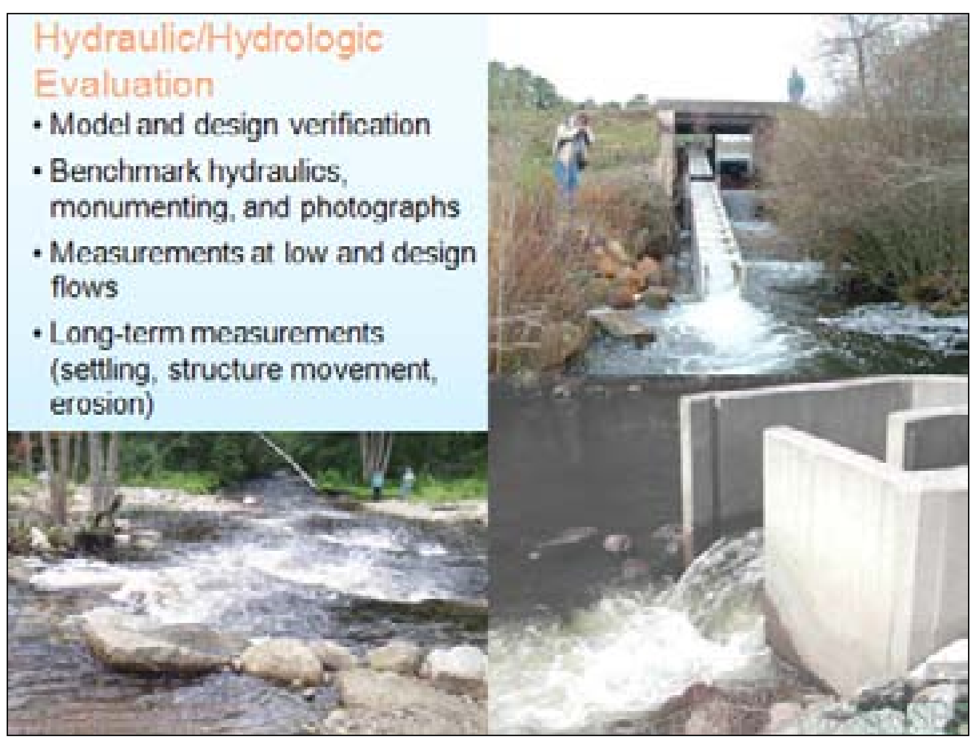


Figure 17-1. Hydraulic/hydrologic modeling overview.

	Identification/ Tracking of Individuals	Cost	Level of Effort	Technical Difficulty	Data Quality
Biological Evaluation					
Observation/Capture					
Visual inspection	No	Low	Low	Low	Low
Trapping/electrofishing	No	Low	Moderate	Low	Moderate
Underwater video	No	Moderate	Moderate	Moderate	Moderate
Hydroacoustics	No	Moderate	Moderate	Moderate	Moderate
Mark-Recapture					
External visual tag/mark	Yes	Low	Moderate	Low	Moderate
PIT Telemetry	Yes	Moderate	Moderate	High	High
Radio Telemetry	Yes	High	Moderate	High	High
Acoustic Telemetry	Yes	High	Moderate	High	High
Advanced Telemetry	Yes	High	High	High	High
Laboratory Studies					
Behavior and hydraulics	Yes	High	High	High	High
Physiological Evaluation					
Mortality, injury, stress	Yes	Moderate	High	High	High
Biological Monitoring					
Live counting	No	Low	Low	Low	High
Video counting	No	Moderate	Low	Moderate	High
Automated counting	No	Moderate	Low	Moderate	Moderate

Table 3. General comparison of associated components of biological evaluation and monitoring. Specifc ratings may change up or down on a case-by-case basis depending on site conditions, specific evaluation and monitoring protocols and individual competency. As technology evolves these ratings will likely change as well.

Biological Evaluation

Basic components of a biological evaluation to assess fish passage efficiency include attraction to the structure, attempts to enter the structure, time required to pass, and the traditional metric of overall percent of fish passed that initially enter the structure. Indirect metrics of physiological stress associated with passage and injuries incurred during passage are considered part of a biological evaluation. Components such as general passage behaviors, swimming speed, predation within the structure, and direct or indirect physical injury or mortality incurred during passage may also be considered; injury and mortality are usually conducted for downstream passage structures, but may be applicable to upstream passage structures as well.

Observation/Capture Techniques: Historically, direct visual observations (without counting fish) have been used as a primary method of evaluation of fish passage structures (Figure 17-2), but this method is not inherently quantitative, and visual observations can often be misleading. Visual documentation of fish within a structure (e.g., entering a fishway, avoiding an intake, descending a downstream bypass, schooling or accumulating within certain zones of the structure, etc.) may indicate that fish are able to use a passage structure, but is generally unreliable for estimating overall passage efficiency. Observations of large numbers of fish within a structure do not take into account the number of fish that are available to be passed, attempting to pass, or that are successful in passing. Visual observations are also often difficult to perform at night or when water conditions are turbid, or at greater water depths. New technologies employing underwater video or acoustic cameras can overcome some of these limitations, yet rarely afford complete coverage of larger structures or associated environments (tailraces and forebays) from which fish are entering a structure, or have limitations in identification of species or individuals. Traps, nets, or electrofishing can be used in a similar manner, but are not as effective or accurate and difficult to use in high flow or high velocity structural environments. Hydroacoustics can also be used to obtain relative counts of fish when visibility is limited, or in large areas like forebays or tailraces (Figure 17-3). However, the data output associated with hydroacoustics makes it difficult to identify fish to species or to obtain accurate, absolute counts of fish observed. Occasionally qualitative observations can indicate improvement of passage performance, as evidenced by a significant increase in relative numbers of fish passing the structure, or a decrease in numbers of fish congregating below (upstream passage structure) or above (downstream passage structure) a structure relative to pre-modification conditions. Visual observations do have value in assessing aspects of behavior of fish to passage structures and their associated hydraulic environments, and can be useful in identifying passage dead-ends, bottlenecks, delays, or sources of fish stress or injury during passage.

Mark-Recapture Techniques: Observation/Capture techniques generally cannot provide data on movements of individual fish. Mark-recapture studies are used to obtain more quantitative data and information on movements of fish, or on rates of passage (Figure 17-4). This approach requires marking individual fish with a unique identifier that can be detected at a later date. However, marks or tags (including telemetry tags) must not interfere with normal migratory, endogenous, or reactive behaviors of fish; i.e., "tag effect" must be minimal. A control group of unmarked and marked fish may be held and employed for observation and evaluation of marking effects.

External marking of fish via fin clipping, dyes, branding, or pigment injection can be performed. External marking can be a low-cost method to tag many fish for mark-recapture studies. However, these methods have limitations in providing unique marks for individual fish and tend to fade or become detached from fish over time. Fish also need to be handled twice: first to mark and second to identify. Fin clips can regenerate or become indistinguishable over long time periods. External numerically coded tags or internal tags (coded wire tags or visual implant tags) overcome some of these limitations and allow rapid marking and visual identification of potentially large numbers of fish. These methods usually still require recapture of fish to examine for presence of tags and to decode the tag identification number. All external marks can also potentially influence fish behavior or susceptibility to disease and predation. External marking and internal tags can require a considerable amount of effort, and recapture rates of even large numbers of marked fish can still be very low at large study sites.

Biotelemetry is currently the preferred option for mark-recapture evaluations. The technique can employ a variety of biotelemetry technologies, including radio tags, acoustic tags, and PIT tags (Figure 17-5). Many of these tags can also include sensors that provide additional data on fish movements and behaviors (e.g., depth, swimming speed). Appropriateness of each technique depends on the type of data desired and physical constraints of the project site under evaluation (e.g., water depth, conductivity, detection range, etc.). Due to the relatively large size of telemetry tags, the technique may not be applicable for smaller fishes, although recent advances have resulted in smaller and longer-term tags. Expense of tags and associated detection equipment often limits the total number of fish that can be tagged for a specific study, and hence the power of subsequent statistical analyses. Telemetry studies require careful thought in their design and implementation in order to provide appropriate data as well as maximize data return.

Laboratory Studies: Fish passage evaluations can also be conducted under a higher degree of experimental control in the laboratory, at both large and small scales (Figure 17-6). A laboratory environment provides an opportunity to control hydraulic variables and rapid or significant alteration of test structures not usually possible in the field. Designs of different passage structures can be compared side-by-side under identical conditions and with fish of the same origin, reducing environmental and behavioral variability associated with field studies. However, lab evaluations require a specialized facility if the structures are large or require high flows. This can potentially make the facility expensive, but some tests can be done at a smaller scale and at less expense.

Laboratory studies usually require collection and transport of fish from various field locations for testing within the facility. Collection and transport of fish usually incurs some level of stress and loss of migratory motivation in fish, which must be minimized or otherwise controlled or accounted for in laboratory experimental designs. Techniques similar to those used in field evaluations (Observation-Capture, Mark-Recapture) can often be employed in laboratory experiments to increase temporal and spatial resolution of data. Laboratories also offer detailed investigations of fish behavior and swimming performance not related to specific structures that are critical to passage design and understanding of fish motivation and attraction to specific structures or hydraulic conditions.

Figure 17-2. Visual inspection methods.

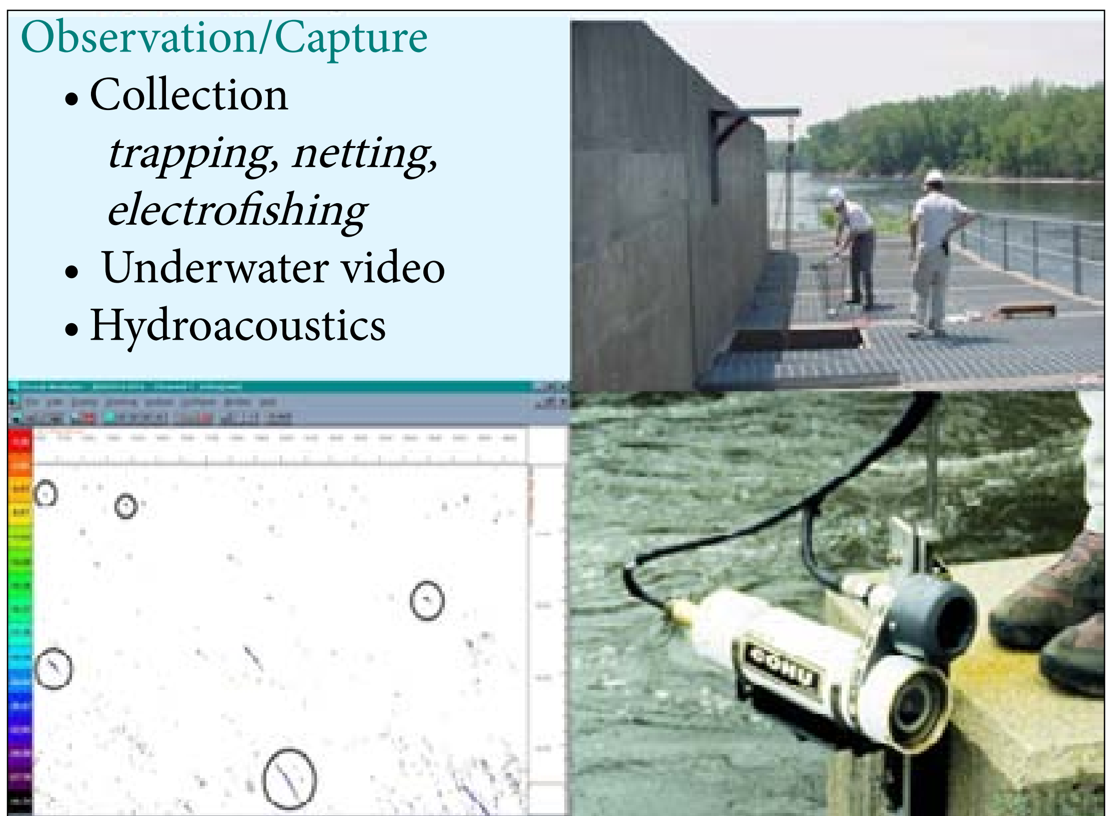


Figure 17-3. Employing typical capture methods, hydroacoustics, and underwater video methods.

Figure 17-4. Mark and recapture tagging and telemetry equipment and methods commonly employed.

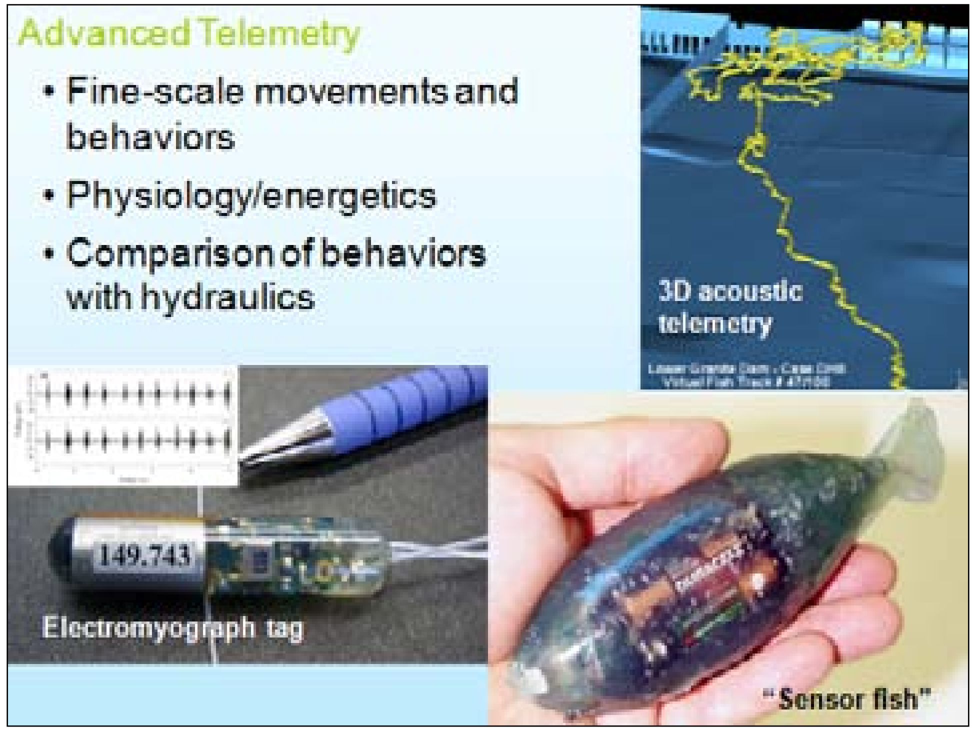


Figure 17-5. *Above:* Advanced telemetry technology under development today. *Below:* New digital sonar/ultrasound technology is under development, with promising ability for observation of fish behavior.

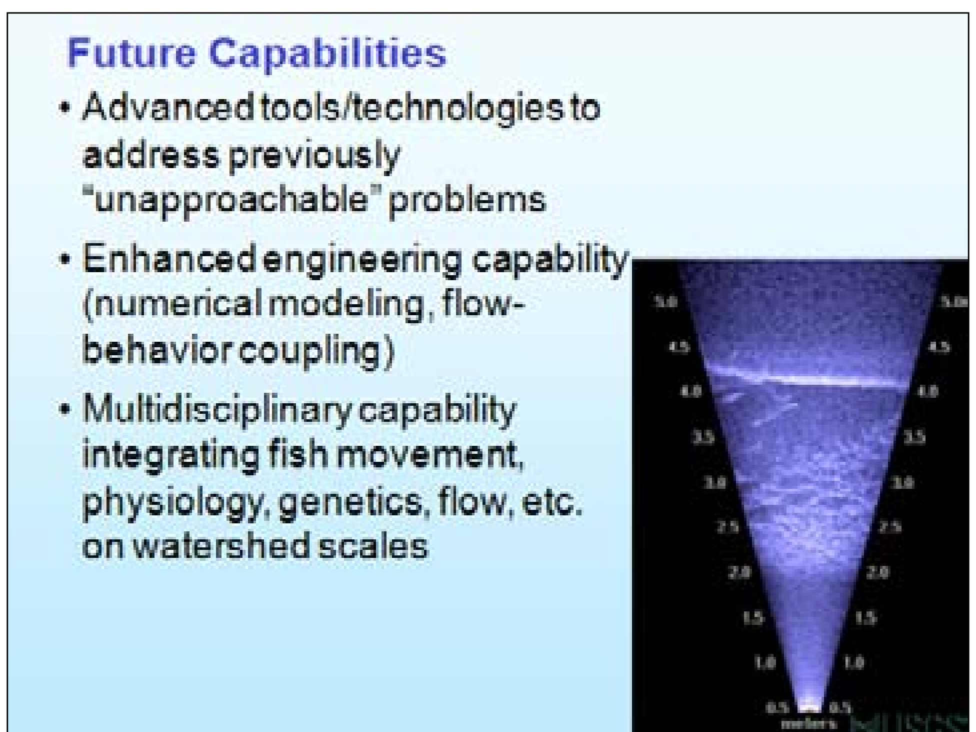


Figure 17-6. Laboratory study of downstream passage bar racks, fishway designs, including a spiral upstream pass for sturgeons.

Physiological Evaluation: Studies of physiology and energetics of fish can be important components of evaluations if passage through a structure is potentially stressful or causes injury or delay. Passage structures that pass a high proportion of fish may still have a net negative effect if they alter the physiology of fish to the degree that reproduction or survival potential are reduced. Such studies may include assessment of blood-borne indicators of stress or high oxygen demand (e.g., cortisol, lactate), pressure change effects (gas-bubble or swimbladder trauma), effects of delay on reproductive capability (gonosomatic index), or seawater tolerance. Indirect effects of injuries to fish caused by structures can also be assessed (e.g., lacerations, scale or mucus loss). Physiological assessment usually requires capturing and rapidly processing fish to take tissue or blood samples. Few studies on physiology of fish passage have been conducted; usually a high level of technical expertise is required.

Data Analysis/Measures of Performance: Methods and data analysis techniques for structure and river reach passage data are diverse; reviews of current methods and more advanced models can be found in Burnham et al. (1987), Castro-Santos and Haro (2003), and Skalski et al. (2009). Relatively simple statistical treatments of data can be applied in some cases (e.g., calculation of percent passage data), but appropriate data treatment is dependent on experimental design, level of replication, sample size, etc. Complex or novel experimental designs or treatments of data might need to receive some level of expert peer review by researchers or statisticians.

Biological Monitoring

Monitoring of passage structures involves accurately assessing numbers and times of passage of all species of fish which transit a structure. Accurate monitoring is often technically challenging given the scales of this task in terms of both number of fish to be counted, identification of individuals passing a physically large site, and the need to monitor continuously throughout an entire season. Typically, visual counts are made at some type of counting structure; often a counting window at fishways, or a downstream bypass sampler (Figure 17-7). Downstream monitoring is particularly problematic in that not all migrants may pass through a monitored bypass, rather passing uncounted via spill or through turbine units. Often, monitoring of downstream passage is only semi-quantitative, yielding only relative indices of abundance and periods of downstream movement.

Accurate visual counting requires clear visual images of fish (i.e., "live" counting or video recording) to ascertain numbers and species identification. Comprehensive "round-the-clock" monitoring can be achieved by video recording, and covert observations of passage of fish at night may be possible with infrared, low-light, or acoustic cameras. More advanced video systems may use machine vision algorithms to count individual fish and even identify fish to species, but the technology is not well developed, and usually expensive. Currently, the ability of computer programs to identify fish to species is limited. Periods of high turbidity may inhibit accurate visual counts, and failures in structure operations (e.g. mechanical lifts, debris loading) may preclude visual and video counting; such events should be recorded and documented in detail. Counting facilities should be well maintained and properly equipped and staffed to make counts as accurate and consistent as possible.

Large numbers of fish may pass through a counting facility at one time, making accurate enumeration of fish difficult. In this case, large numbers may be estimated or otherwise parsed through the structure in smaller numbers so that they can be counted more accurately. This can incur delays in passage or cause fish to "stack up" within a structure. Documentation of counting method and counting conditions (including project operations; e.g., total flows, periods of generation, spill events, etc.) is critical, and standardized methods help ensure counts between seasons are consistent. Counts are typically reported on a daily basis, but hourly (or even sub-hourly) counts of fish may have value in understanding run timing and effect of project operations or other environmental variables on passage performance.

Other monitoring techniques include automated electronic counters which use electrical resistance bridges, infrared beams, or the aforementioned video machine vision systems. The cost of these devices is moderate to high, but they can count fish reasonably accurately if total numbers are relatively low, and other environmental criteria are met. The ability of electronic counters to identify species is limited; usually they are applied when collective counts of only one species that is the only known species to pass in significant numbers (e.g., salmon, blueback herring, alewife) are required. Accurate counting also requires good water clarity and a minimum of debris, and often fish are forced to pass through an electronic counting device one at a time.

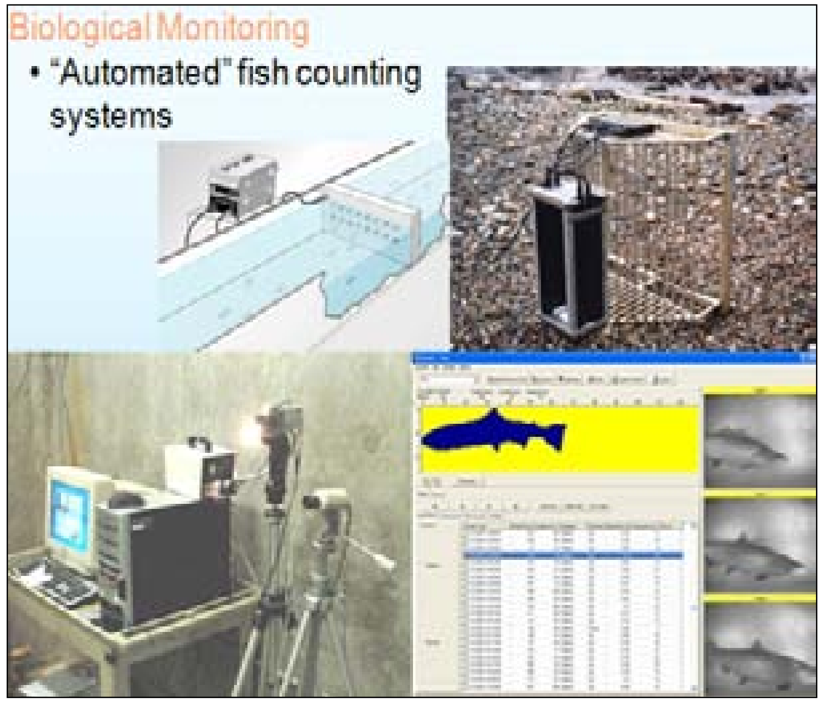


Figure 17-7. Biological monitoring of upstream passage, similar methods may be adapted for downstream passage.

Chapter 18. Operation and Maintenance Planning

Detailed plans for operation and maintenance (O&M Plans) are important to maintain safe, timely, and effective fish passage after construction of upstream and downstream passage facilities. The agency or company responsible for the facility should consider the potential long-term financial commitment and staffing plan necessary to support optimum fish passage, and to ensure effective maintenance and improvements over time. Facility operators should be trained and experienced in fish passage, and be knowledgeable of site specific conditions applicable to the upstream and downstream passage facility, and behavior and migration of important fish species. Most fishways are designed based upon knowledge of other effective passage sites and operations. Operational adjustments are almost always needed to adapt optimum fishway operation to the particular site conditions at a new facility. Fishway operators and fishery agencies generally observe and learn about needed adjustments to achieve best passage success over time. An initial draft O&M Plan is typically developed in consultation with NMFS and/or USFWS and the state fishery resource agency during planning and construction of the fish passage facility. At licensed hydropower projects, under jurisdiction of the FERC, the licensee or owner of the project generally initiates the operation and maintenance plan in coordination with and subject to approval by the fishery resource agencies. Important components O&M Plans have included:

- Design diagrams showing all components of the fishway, with detailed operation instructions for all components.
- Headwater and tailwater rating curves describing water elevations at various flow conditions.
- Locations of staff gages to facilitate observation of flow conditions.
- Routine scheduled maintenance actions.
- Periodic operational inspections of fishway components, flow conditions, debris accumulation as determined to be needed by the review team.
- Annual inspections prior to beginning of the fish migration season.
- Timely plans for restoration or repair of the fishway after flood flows, ice damage, etc.
- Operation of fish data recording/counting systems, if included.
- Listing of fishery agency staff contacts, to be updated as needed.
- Description of agency and company responsibilities to be maintained.
- Provision for operational improvements as experience is gained through fish passage seasons.

References and Suggested Reading

Aadland, L.P. 2010. Reconnecting Rivers: Natural Channel Design in Dam Removals and Fish Passage. Minnesota Department of Natural Resources. Fergus Falls, Minnesota. January 2010.

Aarestrup, K., M.C. Lucas, and J.A. Hansen. 2003. Efficiency of a nature-like bypass channel for sea trout (*Salmo trutta*) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish 12: 160-168.

Adams, R. D. and U.G. Reinhardt. 2008. Effects of texture on surface attachment of spawning run sea lampreys *Petromyzon marinus*: a quantitative analysis. Journal of Fish Biology 73: 1464-1472.

Almeida, P.R.; Quintella, B.R.; Costa, M.J.; Moore, A. (eds.) 2007. Proceedings of the Sixth Conference on Fish Telemetry held in Europe. Hydrobiologia 582: 300p.

Amaral, S.V., J.L. Black, B.J. McMahon and D.A. Dixon. 2002. Evaluation of angled bar racks and louvers for guiding lake and shortnose sturgeon. Pages 197-210 in: Van Winkle, W., P. J. Anders, D. H. Secor, and D. A. Dixon, (eds). Biology, Management, and Protection of North American Sturgeons. American Fisheries Society Symposium 28. Bethesda, Maryland.

Amaral, S.V., F.C. Winchell, B.J. McMahon, and D.A. Dixon. 2003. Evaluation of angled bar racks and louvers for guiding silver phase American eels. American Fisheries Society Symposium 33:367-376.

American Rivers and Trout Unlimited. 2002. Exploring Dam Removal: A Decision Making Guide. 85 pp. http://www.americanrivers.org/library/reports-publications/exploring-dam-removal.html

American Society of Civil Engineers (ASCE). 1995. Guidelines for design of intakes for hydroelectric plants: Committee on Hydropower Intakes. ASCE Publishers. New York, New York. 469 pp

Annett, B.J. 2005. Conservation genetics of remnant anadromous brook trout, *Salvelinus fontinalis*, populations at the southern limit of their distribution: population structure and impacts of historic stocking. Abstract. http://www.ma-ri-tu-council.org/Abstract.htm

Atlantic States Marine Fisheries Commission (ASMFC). 1999. Amendment 1 to the Interstate Fishery Management Plan for Shad and River Herring. Fishery Management Report 35. 77 pp

ASMFC. 2000. Fishery Management Report No. 36. Interstate Fishery Management Plan for the American Eel.

ASMFC. 2003. Amendment 6 to the Interstate Fishery Management Plan for Atlantic striped bass. Fishery Management Report 41. 63 pp

ASMFC. 2009. Amendment 2 to the Interstate Fishery Management Plan for Shad and River Herring (River Herring Management). 166 pp.

ASMFC. 2010. Amendment 3 to the Interstate Fishery Management Plan for Shad and River Herring (American Shad Management). 158 pp.

Atlantic Sturgeon Status Review Team. 2007. Status review of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*). Report to National Marine Fisheries Service, Northeast Regional Office on February 23, 2007.

Baker, C.O. and F.E. Votapka. 1990. Fish Passage Through Culverts. Federal Highways Administration & USDA Forest Service. FHWA-FL-90-006. (Available from USDA Forest Service publications, San Dimas laboratory, California).

Baras E., B. Salmon and J.C. Philippart, 1994. Evaluation of a eel trap sampling method for the assessment of migrant yellow eels *Anguilla anguilla* (L) in the River Meuse. Bulletin Français de Pêche et de la Pisciculture 335: 7-16.

Barbin, G.P. and W.H. Krueger. 1994. Behaviour and swimming performance of elvers of the American eel, *Anguilla rostrata*, in an experimental flume. Journal of Fish Biology 45(1):111-121.

Bates, D.W., and R. Vinsonhaler. 1956. Use of louvers for guiding fish. Transactions of the American Fisheries Society 86:38–57.

Bates, K.M. 1988. Screen Criteria for Juvenile Salmon, Washington Department of Fisheries. Olympia, Washington.

Bates, K.M. 1992. Fishway Design Guidelines for Pacific Salmon, from Fish Passageways and Diversion Structures, U.S. Fish and Wildlife Service National Education and Training Center.

Bates, K.M. 1993. Fish passage policy and technology – Proceedings of a symposium sponsored by the Bioengineering Section of the American Fisheries Society, Portland, Oregon

Bates, K.M. 2000. Draft Fishway Guidelines for Washington State. Washington Department of Fish and Wildlife, Olympia, Washington.

Bell, M.C. 1991. Fisheries handbook of engineering requirements and biological criteria. Fish Passage and Development Evaluation Program, U.S. Army Corps of Engineers, Portland, Oregon.

Brown, L.S. 2005. Characterizing the downstream passage behavior of silver phase American eels at a small hydroelectric facility. M.Sc. Thesis, Department of Natural Resource Conservation, University of Massachusetts, Amherst, Massachusetts. 110 pp.

Brown, L., A. Haro, and T. Castro-Santos. 2009. Three-dimensional movement of silver-phase American eels in the forebay of a small hydroelectric facility. Pages 277-291 *in*: J. Casselman et al. editors. Eels at the Edge: Science, Status, and Conservation Concerns. American Fisheries Society, Bethesda, Maryland.

Bruijs M.C.M., and C.M.F. Durif. 2009. Silver eel migration and behaviour. Pages 65-95 in: G. van den Thillart et al. (eds.), Spawning Migration of the European Eel. Springer Science + Business Media B.V.

Buckley, J.L. 1989. Species profiles: life histories and environment; requirements of coastal fishes and invertebrates (North Atlantic) - rainbow smelt. U.S. Fish Wildlife Service. Biological Report. 82(11.106).

Bult, T.P., and W. Dekker 2007. Experimental field study on the migratory behaviour of glass eels (*Anguilla anguilla*) at the interface of fresh and salt water. - ICES Journal of Marine Science, 64:1396-1401.

Burnham, K.P., D.R. Anderson, G.C. White, C. Brownie, and K. Pollock. 1987. Design and analysis methods for fish survival experiments based on release–recapture. American Fisheries Society, Monograph 5, Bethesda, Maryland.

Cada, G.F. 1998. Fish passage mitigation at hydroelectric power projects in the United States, pp. 208-219. In: Fish Migration and Fish Bypasses: Proceedings of the Symposium. (Jungwirth, M., S. Schmutz, and S. Weiss, Eds.). Vienna, Austria: Fishing News Books.

Calles, E.O., and L.A. Greenberg 2005. Evaluation of nature-like fishways for re-establishing connectivity in fragmented salmonid populations in the river Eman. River Research and Applications 21: 951-960.

Castro-Santos, T. and A. Haro. 2003. Quantifying migratory delay: a new application of survival analysis methods. Canadian Journal of Fisheries and Aquatic Sciences 60: 986-996.

Castro-Santos, T., A. Cotel, and P. Webb. 2009. Fishway evaluations for better bioengineering—an integrative approach. Pages 557-575 in: Haro, A. J., K. L. Smith, R. A. Rulifson, C. M. Moffitt, R. J. Klauda, M. J. Dadswell, R. A. Cunjak, J. E. Cooper, K. L. Beal, and T. S. Avery, editors. 2009. Challenges for Diadromous Fishes in a Dynamic Global Environment. American Fisheries Society, Symposium 69, Bethesda, Maryland.

Cheong, T.S., M.L. Kavvas, and E.K. Anderson. 2006. Evaluation of adult white sturgeon swimming capabilities and applications to fishway design. Environmental Biology of Fishes 77:197-208.

Christie, G.C. and C.I. Goddard. 2003. Sea lamprey International Symposium (SLIS II): advances in the integrated management of sea lamprey in the Great Lakes. Journal of Great Lakes Research 29(Supplement 1):1-14.

Clay, C.H. 1995. Design of Fishways and Other Fish Facilities. Boca Raton, Florida: CRC Press.

Clayton, G.R. 1976. Reproduction, first year growth, and distribution of anadromous rainbow smelt, *Osmerus mordax*, in the Parker River and Plum Island Sound Estuary, Massachusetts. M.S. Thesis. University of Massachusetts, Amherst. 102 pp.

Collins, M.R., D. Cooke, B. Post, J. Crane, J. Bulak, T.I.J. Smith, T.W. Greig, J.M. Quattro. 2003. Shortnose sturgeon in the Santee-Cooper reservoir system, South Carolina. Transactions of the American Fisheries Society 132:1244-1250.

Cooke, D.W., and S.D. Leach, and J.J. Isely. 2002. Behavior and lack of upstream passage of shortnose sturgeon at a hydroelectric facility and navigation lock complex. American Fisheries Society Symposium 28:101-110.

Coutant, C.C. (Ed.). 2001. Behavioral technologies for fish guidance. American Fisheries Society, Symposium 26, Bethesda, Maryland.

Daborn, G.R., G.C. Baker, and M.J. Dadswell. 1984. Environmental consequences and ameliorative measures of the Annapolis tidal power project. Water Science & Technology. 16:297-306.

Dadswell, M.J., B.D. Taubert, T.S. Squiers, D. Marchette, and J. Buckley. 1984. Synopsis of biological data on shortnose sturgeon, *Acipenser brevirostrum* Lesueur 1818. National Oceanic and Atmospheric Administration Technical Report National Marine Fisheries Service 14. 45 pp.

Desrocher, D. 1994. Suivi de la migration de l'anguille d'Amérique au complexe Beauharnois. Report Vice présidence Environnement, Hydro-Québec, Montréal, Canada.

Dittman, A.H., T.P. Quinn, and G.A. Nevitt. 1996. Timing of imprinting to natural and artificial odors by coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences 53(2):434-442.

Dixon, D.A., editor. 2003. Biology, management, and protection of catadromous eels. American Fisheries Society, Symposium 33, Bethesda, Maryland.

Dumont, U. 2007. Design of roughened channels for fish passage. Floecksmuehle Consultants, Aachen, Germany. 12 pp.

Durif C, P. Elie, C. Gosset, J. Rives, and F. Travade. 2003. Behavioral study of downstream migrating eels by radio-telemetry at a small hydroelectric power plant. Pages 343-356 *in*: D. A. Dixon (ed.) Biology, Management, and Protection of Catadromous Eels. American Fisheries Society, Symposium 33, Bethesda, Maryland.

DWA (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V). 2006. Fish Protection Technologies and Downstream Fishways: Dimensioning, Design, Effectiveness Inspection. German Association for Water, Wastewater and Waste, Hennef. 228 pp.

Eberstaller, J., M. Hinterhofer, and P. Parasiewicz. 1998. The effectiveness of two nature-like bypass channels in an upland Austrian river. Pages 363-383 *in* Jungwirth, M., S. Schmutz, and S. Weiss, editors. Fish Migration and Fish Bypasses. Fishing News Books, Oxford.

Eicher, G., 1987. Turbine-related fish mortality: review and evaluation of studies, Report EPRI AP-5480, Palo Alto, California.

Ely, P. C., S. P. Young, and J. J. Isely. 2008. Population size and relative abundance of Alabama shad reaching Jim Woodruff lock and Dam. Apalachicola River, Florida. North American Journal of Fisheries Management 28:827-831.

Electric Power Research Institute (EPRI). 1998a. Review of Downstream Fish Passage and Protection Technology Evaluations and Effectiveness. Prepared by Alden Research Laboratory, Inc., EPRI Report No. TR-111517.

EPRI. 1998b. Evaluation of Fish Behavioral Barriers. Prepared by Alden Research Laboratory, Inc., EPRI Report No. TR-109483. EPRI (Electric Power Research Institute). 2001. Review and documentation of research and technologies on passage and protection of downstream migrating catadromous eels at hydroelectric facilities. EPRI Report Number 1000730. Palo Alto, California.

EPRI. 2001. Review and documentation of research and technologies on passage and protection of downstream migrating catadromous eels at hydroelectric facilities. EPRI Report Number 1000730. Palo Alto, California.

Euston, E. T., D. D. Royer, and C. Simons. 1997. Relationship of emigration of silver American eels (*Anguilla rostrata*) to environmental variables at a low head hydro station. Waterpower 97: 549-558.

Fay, C., M. Barton, S. Craig, A. Hecht, J. Pruden, R. Sanders, T. Sheehan, and J. Trial. 2006. Status Review for Anadromous Atlantic Salmon (*Salmo salar*) in the United States. Report to the National Marine Fisheries Service and U.S. Fish and Wildlife Service. 294 pp.

Federal Energy Regulatory Commission (FERC). 2004. Evaluation of mitigation effectiveness at hydropower projects: fish passage. Draft report 2004 1008-0140, Office of Energy Projects, Division of Hydropower Administration and Compliance, Washington D.C.

FERC. 2003a. Final environmental assessment: Application for surrender of project license, Ft. Halifax Project. FERC NO. 2552-258. Sebasticook River, Maine.

FERC. 2003b. Order issuing subsequent license for the S.D. Warren Company Projects. FERC Nos. 2897, 2931, 2932, 2941, and 2942. Presumpscot River, Maine.

FERC 2004. Evaluation of mitigation effectiveness at hydropower projects: fish passage. Division of Hydropower Administration and Compliance. Office of Energy Projects.

FERC. 2010. Final environmental assessment: Application for surrender of license, Veazie, Great Works, and Howland. FERC Project Nos. 2403-056, 2313-019 and 2721-020. Maine.

Federal Highway Administration (FHA). 2007. Design for fish passage at roadway-stream crossings: synthesis report. U.S. Department of Transportation Publication No. FHWA-HIF-07-033. 280 pp.

Food and Agriculture Organization of the United Nations and Deutscher Verband für Wasserwitschaft und Kulturbau e.V (FAO/DVWK). 2002. Fish passes – design, dimensions, and monitoring. FAO, Rome

Foster, J.R. and C.B. Schom. 1989. Imprinting and homing of Atlantic Salmon (*Salmo salar*) kelts. Canadian Journal of Fisheries and Aquatic Sciences 46: 714-719.

Franke, G.F., D.R. Webb, R.K. Fisher, D. Mathur, P.N. Hopping,, P.A. March, M.R. Headrick, I.T. Laczo, Y. Ventikos, and F. Sotiropoulos. 1997. Development of environmentally advanced hydropower turbine system design concepts. Voith Hydro, Inc. Report No. 2677-0141. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Franklin, A.E., A. Haro, T. Castro-Santos, and J. Noreika. In Prep. Evaluation of nature-like and technical fish passes for the passage of alewife (*Alosa pseudoharengus*) at two coastal streams in New England. To be submitted to Transactions of the American Fisheries Society.

Graf, W.L. 1993. Landscapes, commodities, and ecosystems: The relationship between policy and science for American rivers. Pp. 11–42 *in* Sustaining Our Water Resources. Washington, D.C.: National Academy Press.

Graf, W.L. (Editor) 2002. Dam Removal Research: Status and Prospects. Proceedings of the Heinz Center dam removal workshop. Oct. 2002. Heinz Center. Washington, D.C.

Greene, K.E., J.L. Zimmerman, R.W. Laney, and J.C. Thomas-Blate. 2009. Atlantic coast diadromous fish habitat: A review of utilization, threats, recommendations for conservation, and research needs. Atlantic States Marine Fisheries Commission Habitat Management Series No. 9, Washington, D.C. 463 p.

Grunwald, C., L. Maceda, J. Waldman, J. Stabile,and I. Wirgin. 2007. Conservation of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*: delineation of stock structure and distinct population segments. Conservation Genetics 9:1111-1124.

Gulf States Marine Fisheries Commission (GSMFC). 2006. Striped bass fishery of the Gulf of Mexico, United States: a regional management plan. Publication No. 137.

Halliwell, D. 2009. Current status of native/wild brook trout in New England freshwaters. Paper No. 52-5. Northeastern Section – 44th Annual Meeting, Geological Society of America . Vol. 41 (3): 104. http://gsa.confex.com/gsa/2009NE/finalprogram/abstract_155581.htm

Haro, A. 2003. Downstream migration of silver-phase anguillid eels. Pages 215-222 *in*: Aida, K., K. Tsukamoto, and K. Yamauchi, eds. Eel Biology. Springer, Tokyo.

Haro, A., T. Castro-Santos, K. Whalen, G. Wipplehauser and L. McLaughlin. 2003. Simulated effects of hydroelectric project regulation on mortality of American eels. Pages 357- 365 *in*: D. Dixon, editor. Biology, Management, and Protection of Catadromous Eels. American Fisheries Society Symposium 33. Bethesda, Maryland.

Haro, A., T. Castro-Santos, J. Noreika, and M. Odeh. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Canadian Journal of Fisheries and Aquatic Science 61: 1590-1601.

Haro, A., A. Franklin, T. Castro-Santos and J. Noreika. 2008. Design and evaluation of nature-like fishways for passage of northeastern diadromous fishes. U.S. Geological Survey Biological Resources Discipline, S.O. Conte Anadromous Fish Research Laboratory (CAFRL). Final Report submitted to NOAA National Marine Fisheries Service Office of Habitat Conservation. 35 pp.

Haro, A. and B. Kynard. 1997. Video evaluation of passage efficiency of American shad and sea lamprey in a modified Ice Harbor fishway. North American Journal of Fisheries Management 17: 981-987.

Haro, A., M. Odeh, J. Noreika, and T. Castro-Santos. 1998. Effect of water acceleration on downstream migratory behavior and passage of Atlantic salmon juvenile salmonids and juvenile American shad at surface bypasses. Transactions of the American Fisheries Society 127: 118-127.

Haro, A., W. Richkus, K. Whalen, A. Hoar, W.D, Busch, S. Lary, T. Brush, and D. Dixon. 2000. Population decline of the American eel: Implications for research and management. Fisheries 25: 7-16.

Heinrich, J.W., K.M. Mullett, M.J. Hansen, J.V. Adams, G.T Klar, D.A. Johnson, G.C. Christie, and R.J. Young. 2003. Sea lamprey abundance and management in Lake Superior, 1957 to 1999. Journal of Great Lakes Research 29(Supplement 1):566-583.

Hightower, J.E. and R. Wong. 1997. Potential benefits to anadromous fishes of providing fish passage within the Roanoke River basin. Report to the U.S. Fish and Wildlife Service and Virginia Power. 30 pp.

Hunter, L.A. and L. Mayor. 1986. Analysis of fish swimming performance data, Volume I.

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

Johnson, R.L., and L.Z. Perkins. 1968. Fish ladders for John Day Dam, Columbia River, Oregon and Washington; hydraulic model investigations. U.S. Army Corps of Engineers, North Pacific Division, Technical Report 103-1, Bonneville, Oregon.

Jungwirth, M.S., Schmutz, and S. Weiss (editors). 1998. Fish migration and fish bypasses. Proceedings of a symposium. Blackwell Science Ltd Publisher. Fishing News Books, Oxford, UK.

Kamula, R. 2001. Flow over weirs with application to fish passage facilities. Department of Process and Environmental. Engineering. University of Oulu. Finland.

Kano, R.M. 1982. Responses of Juvenile Salmon and American Shad to Long Term Exposure to Two-Vector Velocity Flows. Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary, Technical Report No. 4, Stockton, California.

Karp, C., L. Hess, and C. Liston. 1995. Re-evaluation of louver efficiencies for juvenile chinook salmon and striped bass, 1993. Tracy Fish Collection Facility Studies. Volume 3. U.S. Bureau of Reclamation, Mid-Pacific Region and Denver Technical Service Center. 31 pp.

Katopodis, C. 1992. Introduction to Fishway Design. Freshwater Institute, Central and Arctic Region, DFO 501 University Crescent Winnipeg, Manitoba Canada, R3T 2N6

Katopodis, C., and N.Rajaratnam. 1983. A review and laboratory study of the hydraulics of Denil fishways. Canadian Technical Report 1/45, Department of Fisheries and Aquatic Sciences.

King, T.L. 2009. Identifying the fundamental unit of management and distinct population segments in Atlantic sturgeon (*Acipenser oxyrinchus*): a genetic-based approach. (abstract). First Symposium on Atlantic Sturgeon – A regional approach to Atlantic sturgeon recovery. Seaboard Fisheries Institute.

Kircheis, F.W. 2004. Sea lamprey Petromyzon marinus Linnaeus 1758. F.W. Kircheis L.L.C., Carmel, Maine. 25 pp.

Knights, B.and E.M. White 1998. Enhancing immigration and recruitment of eels: the use of passes and associated trapping systems. Fisheries Management & Ecology 5(6):459-471.

Kocik, J.F., and T.F. Sheehan. 2006. Atlantic salmon (*Salmo salar*). Status of fishery resources off the northeastern US. NEFSC – Resource Evaluation and Assessment Division. NOAA. http://www.nefsc.noaa.gov/sos/spsyn/af/salmon/

Kynard, B. 1997. Life history, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. Environmental Biology of Fishes 48: 319-334.

Kynard, B. and M. Horgan. 2001. Guidance of yearling shortnose and pallid sturgeon using vertical bar rack and louver arrays. North American Journal of Fisheries Management 21:561–570.

Larinier, M. 1990. Experience in fish passage in France: fish pass design criteria and downstream migration problems. In: Proceedings of the International Symposium on Fishways '90, Gifu, Japan.

Larinier, M. 1992a. Passes à bassins successifs, prébarrages et rivières artificielles. In: Bulletin Français de Pêche et de la Pisciculture. Vol. 326-327: 45-72.

Larinier, M. 1992b. Les passes à ralentisseurs. In: Bulletin Français de Pêche et de la Pisciculture. Vol. 326-327: 73-94.

Larinier, M. 1998. Upstream and downstream fish passage experience in France. In: Fish migration and fish bypasses (editors M. Jungwirth, S. Schmutz and S. Weiss). Fishing News Books, Blackwell Science Ltd Publisher.

Larinier, M. and J. Dartiguelongue. 1989. La circulation des poissons migrateurs: le transit à travers les turbines des installations hydroélectriques. In: Bulletin Français de Pêche et de la Pisciculture. Vol. 312-313: 94p.

Larinier, M., J.P. Porcher, F. Travade and C. Gosset. 1994. Passes à poissons: expertise, conception des ouvrages de franchissement. Collection "Mise au point". Conseil Supérieur de la Pêche, Paris, France.

Larinier, M. and F. Travade. 1999. La dévalaison des migrateurs: problèmes et dispositifs. In: Bulletin Français de Pêche et de la Pisciculture. Vol. 353/354: 181-210.

Larinier, M. and F. Travade. 2002. Design of fishways for shad. In: Bulletin Français de Pêche et Pisciculture. Vol. 364 supplement: 135-146.

Lawson, J. 1709. A new voyage to Carolina; containing the exact description and natural history of that country: together with the present state thereof. And a journal of a thousand miles, travel'd thro' several nations of Indians. Giving a particular account of their customs, manners, etc. London." Reprint edition, Readex Microprint Corporation.

Lorio, W. 2000. Proceedings of the Gulf of Mexico sturgeon (*Acipenser oxyrinchus desotoi*) status of the subspecies workshop. Mississippi State University, Stennis Space Center, Mississippi.

Mader, H., G. Unfer, and S. Schmutz. 1998. The effectiveness of nature-like bypass channels in a lowland river, the Marchfeldkanal. Pages 384-402 *in* Jungwirth, M., S. Schmutz, and S.Weiss, editors. Fish Migration and Fish Bypasses. Fishing News Books, Oxford.

Maine Department of Marine Resources (MEDMR). 2010. Kennebec River Anadromous Fish Restoration Annual Progress Report: 2009. Bureau of Sea Run Fisheries and Habitat.

Maine Department of Transportation (Maine DOT). 2007. Design guide for fish passage through culverts. 61 pp.

Massachusetts Department of Fish and Game (MDFG). 2006. Species Profile: Rainbow Smelt. http://www.mass.gov/dfwele/dmf/recreationalfishing/smelt.htm

McDonald, M. 1887. The River Fisheries of the Atlantic States: The rivers of eastern Florida, Georgia, and South Carolina. Report of the U.S. Commission of Fish & Fisheries. Mis. Doc. 124. Pp. 613-625.

McGrath, K.T. Desrochers, D., Fleury, C. & Dembeck, J.W. (2003). Studies of Upstream Migrant American Eels at the Moses-Saunders Power Dam on the St. Lawrence River near Massena, New York. Biology, Management, and Protection of Catadromous Eels. American Fisheries Society Symposium 33, 153-166.

Meyer, E. 2009. Juvenile Fish Bypass Systems. *In*: Design of Fish Passage Facilities, A Workshop by: National Marine Fisheries Service, Portland, Oregon, June 1-5, 2009

Meyers, T.F. 1994. The Program to Restore Atlantic Salmon to the Connecticut River. *In*: S. Calabi and A. Stout (editors). A Hard Look At Some Tough Issues. Newburyport, Massachusetts, USA: New England Salmon Association Publisher.

Milieu Inc. 2007. Operation and monitoring of the eel-passage facility at the Robert Moses power dam in 2006. New York Power Authority. St. Lawrence-FDR power project. Milieu Inc. La Prairie, Quebec, Canada. 188 pp.

Monk, B., R. Weaver, C. Thompson, and F. Ossiander. 1989. Effects of flow and weir design on the passage behavior of American shad and salmonids in an experimental fish ladder. North American Journal of Fisheries Management 9: 60-67.

Mooney, D.M., C. L. Holmquist-Johnson, and S. Broderick. 2007. Rock ramp design guidelines. U.S. Department of the Interior, Bureau of Reclamation Technical Service Center, Denver, Colorado. 110 pp.

Moser, M.L., P.A. Ocker, L.C. Stuehrenberg and T.C. Bjornn. 2002. Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, USA. Transactions of the American Fisheries Society 131:956-965.

National Marine Fisheries Service (NMFS). 2007. Species of Concern. Rainbow smelt *Osmerus mordax*. http://www.nmfs.noaa.gov/pr/species/fish/rainbowsmelt.htm

NMFS. 2008(a). Species of Concern. Alabama shad (*Alosa alabamae*). http://www.nmfs.noaa.gov/pr/pdfs/species/alabamashad_highlights.pdf

NMFS. 2008(b). Anadromous Salmonid Passage Facility Design. NMFS, Northwest Region, Portland, Oregon.

NMFS. 2009a. NOAA Habitat Program: NMFS Strategic Plan 2009-2013.

NMFS. 2009b. Species of Concern. River Herring (alewife and blueback herring) *Alosa pseudoharengus* and *A. aestivalis*. www.nmfs.noaa.gov/pr/pdfs/species/riverherring_detailed.pdf

NMFS. 2009c. Endangered Species Act Biological Opinion for the Surrender of Licenses for the Veazie, Great Works and Howland Projects, Nos. 2403, 2312, 2721. December 23, 2009.

National Oceanic and Atmospheric Administration and U.S. Fish and Wildlife Service. 1991. Threatened Status for the Gulf Sturgeon (*Acipenser oxyrinchus desotoi*). 56 CFR 49653. September 30, 1991.

Nicholson, L. (editor). 1986. Striped Bass Fishery Management Plan-Gulf of Mexico. Gulf States Marine Fisheries Commission. Publication Number 16. Ocean Springs, Mississippi.

Nislow, K.H. and B.E. Kynard. 2009. The role of anadromous sea lamprey in nutrient and material transport between marine and freshwater environments. American Fisheries Society Symposium 69:485-494.

Nordlund, B. 2009. Upstream Passage. *In*: Design of Fish Passage Facilities, a Workshop by: National Marine Fisheries Service, Portland, Oregon. June 1-5, 2009.

North Carolina Division of Marine Fisheries (NCDMF). 2010. Striped bass Central/Southern Management Area. http://www.ncfisheries.net/stocks/stripedbassCSMA.htm

Odeh. M. (Editor). 1999. Innovations in fish passage technology. Bethesda, Maryland: American Fisheries Society.

Odeh. M. (Editor). 2000. Advances in fish passage technology. Bethesda, Maryland: American Fisheries Society.

Odeh, M. and C. Orvis, 1998. Downstream Fish Passage Facilities Design Considerations and Development at Hydroelectric Projects in the North-east USA. *In*: Fish migration and fish bypasses (editors M. Jungwirth, S. Schmutz and S. Weiss). Fishing News Books, Blackwell Science Ltd Publisher. Oxford, UK. Office of Technology Assessment (OTA). 1995. Fish passage technologies: protection at hydroelectric facilities. Report OTA-ENV-641, Washington D.C.

Ogden, J.C. 1970. Relative abundance, food habits, and age of the American eel, *Anguilla rostrata* (LeSueur), in certain New Jersey streams. Transactions of the American Fisheries Society 99:54-59.

O'Leary, J.A. and B. Kynard. 1983. Movements of radio-tagged fish during studies of down running adult American shad in the Holyoke Dam canal system - 1982. Final Report to NE Utilities Service, Hartford, Connecticut.

Osborn, J.F. 1987. Fishways – historical assessment of design practices. American Fisheries Society Symposium 1:122-130.

Parasiewicz, P., J. Eberstaller, S. Weiss and S. Schmutz. 1998. Conceptual Guidelines for Natural-like Bypass Channels. *In*: Fish migration and fish bypasses (editors M. Jungwirth, S. Schmutz and S. Weiss). Fishing News Books, Blackwell Science Ltd Publisher. Oxford, UK.

Peake, S., F. W.H. Beamish, R.S. McKinley, D.A. Scruton, and C. Katopodis. 1997. Relating swimming performance of lake sturgeon, *Acipenser fulvescens*, to fishway design. Canadian Journal of Fisheries and Aquatic Science 54: 1361-1366.

Porcher, J.P. 1992. Les passes à anguilles. In: Bulletin Français de Pêche et de la Pisciculture 326-327: 134-141.

Porcher, J.P. 2002. Fishways for eels. Bulletin Français de Pêche et de la Pisciculture. 364 Supplement.147-155.

Quinn, R. F. 1994. Fish Passage Facilities for *Alosa*. Anadromous *Alosa* Symposium, 1994. American Fisheries Society. Tidewater Chapter.

Rainey, W.S. 1985. Considerations in the Design of Juvenile Bypass Systems. *In*: Symposium on Small Hydropower and Fisheries. Denver, Colorado. May 1-3, 1985

Rajaratnam, N. and C. Katopodis. 1984. Hydraulics of Engineering 110:1219-1233.

Rajaratnam, N, G.Van der Vinne, and C. Katopodis. 1986. Hydraulics of vertical slot fishways, Journal of Hydraulic Engineering, Vol. 112, No. 10, pp. 909-927, (DOI 10.1061/(ASCE)0733-9429(1986)112:10(909))

Reading, H.H. 1982. Passage of Juvenile Chinook Salmon and American Shad Through Various Trashrack Bar Spacings. State of California Department of Fish and Game Technical Report 5, Interagency Ecological Study Program for the Sacramento-San Juaquin Estuary. Red Bluff, California.

Renaud, C.B. 1997. Conservation status of Northern Hemisphere lampreys (Petromyzontidae). Journal of Applied Ichthyology 13:143-148.

Richkus, W.A. and D.A. Dixon. 2003. Review of research and technologies on passage and protection of downstream migrating catadromous eels at hydroelectric facilities. Pages 377–388 *in*: D. A. Dixon (ed.) Biology, Management, and Protection of Catadromous Eels. American Fisheries Society, Symposium 33, Bethesda, Maryland.

Rizzo, B. 1969. Fish passage facilities design parameters for Connecticut River dams. Turners Falls dam. Bureau of Sport Fisheries and Wildlife, Boston, Massachusetts. 33pp.

Rizzo, B. 1994. Notes and fish passage design information. Fish Passageways and Diversion Structures Course Manual, USFWS Fisheries Academy.

Rizzo, B. 2002. USFWS Fish Passage Facilities Design, Siting and Sizing Criteria, and Standards Used in Northeast Region 5, 1986 – 2002

Rohde, F.C., R.G. Arndt, J.W. Foltz, and J.M. Quattro. 2009. Freshwater fishes of South Carolina. The University of South Carolina Press, Columbia. 430 pp.

Santos, J.M., M.T. Ferreira, F.N. Godinho, and J. Bochechas. 2005. Efficacy of a nature-like bypass channel in a Portuguese lowland river. Journal of Applied Ichthyology 21: 381-388.

Saunders, R., M. A. Hachey, and C. W. Fay. 2006. Maine's diadromous fish community: past, present, and implications for Atlantic salmon recovery. Fisheries 31:537–547.

Skalski, J.R., R.A. Buchanan, and R. L. Townsend. 2009. A multiple-release model to estimate route-specific and dam passage survival at a hydroelectric project. North American Journal of Fisheries Management 29:670–679. Schmutz, S., C. Giefing, and C. Wiesner. 1998. The efficiency of a nature-like bypass channel for pike-perch (*Stizostedion lucioperca*) in the Marchfeldkanalsystem. Hydrobiologia 372: 355-360.

Solomon D.J. and M.H. Beach. 2004a. Fish pass design for eel and elver (*Anguilla anguilla*). R&D Technical Report W2-070/TR1. Environment Agency UK. 92 pp.

Solomon D.J. and M H Beach. 2004b. Manual for provision of upstream migration facilities for eel and elver. Science Report SC020075/SR2. Environment Agency UK. 63 pp.

Stevenson, C.H. 1899. The shad fisheries of the Atlantic coast of the United States. U.S. Fish Commission Report for 1898. Pp. 101-269

Stira, R.J. and D.A. Robinson. 1997. Effectiveness of a Louver Bypass System for Downstream Passage of Atlantic Salmon Smolts and Juvenile Clupeids in the Holyoke Canal, Connecticut River, Holyoke, Massachusetts. *In*: Fish Passage Workshop, Milwaukee, Wisconsin, May 6-8, 1997

Sulak, K.J. and J.P. Clugston. 1999. Recent advances in life history of Gulf of Mexico sturgeon, *Acipenser oxyrinchus desotoi*, in the Suwannee River, Florida, USA: a synopsis. Journal of Applied Ichthyology 15:116-128.

Taft, E.P. 2000. Fish protection technologies: a status report. Environmental Science & Policy 3 (2000): S349-S359.

Tesch F.-W. 1977. The Eel - biology and management of anguillid eels. Chapman and Hall, London.

Travade, F. and M. Larinier. 2002. Monitoring techniques for fishways. Bulletin Français de Pêche et de la Pisciculture. 364 Supplement. 166-178.

U.S. Army Corps of Engineers. 1977. Fish ladder for Charles River Dam, Charles River, Massachusetts; hydraulic model investigation. U.S. Army Corps of Engineers, North Pacific Division, Technical Report 157-1, Bonneville, Oregon.

U. S. Bureau of Reclamation (USBR). 2006. Fish protection at water diversions: a guide for planning and designing fish exclusion facilities. Water Resources Technical Publication. 480 pp.

U.S. Fish and Wildlife Service (USFWS). 1994. Notes and fish passage design information. Fish Passageways and Diversion Structures Course Manual USFWS Fisheries Academy.

USFWS. 2000. Fish Passageways and Bypass Facilities – East. U.S. Fish and Wildlife Service National Conservation Training Center Training Notebook. July 10-14, 2000, Hadley Massachusetts.

USFWS. 2007. Fish Facts – Sea Lamprey. Connecticut River Coordinator's Office. http://www.fws.gov/r5crc/Fish/zi_pema.html

USFWS and NMFS. 2009. Gulf sturgeon (*Acipenser oxyrinchus desotoi*). 5-year review: summary and evaluation. September 2009. 49 pp.

Verdon, R., D. Desrochers, and P. Dumont. 2003. Recruitment of American eels in the Richelieu River and Lake Champlain: Provision of upstream passage as a regional-scale solution to a large-scale problem. American Fisheries Symposium. Biology, Management, and Protection of Catadromous Eels. 33, 125-138.

Warren, J.J., L.G. Beckman, and I.J. Donaldson. 1993. Fishway use by White Sturgeon on the Columbia River. Washington Sea Grant Program, WSG-AS 93-02.

Watson, H.L. 1996. The Common Rights of Mankind: Subsistence, Shad, and Commerce in the Early Republican South. Journal of American History 83(1):13-43.

Weaver, C.R., and C.S. Thompson, and F.J. Ossiander. 1972. Evaluation of fish passage in the vertical slot regulating section of the south shore ladder at John Day Dam. Final Report (Contract NPPSU-PR-71-2509) to U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Weiland, M.A. and T.J. Carlson. 2003. Technologies for evaluating fish passage through turbines. Pacific Northwest National Laboratory Report No. PNNL-14437. 85 pp.

White, R.G., and B. Mefford. 2002. Assessment of behavior and swimming ability of Yellowstone River sturgeon for design of fish passage devices. Internal Report, U.S. Bureau of Reclamation Water Resources Research Laboratory, Denver, Colorado. 40 pp.

Appendix I. Definition of Terms

The following terms are identified in italics throughout the document text to aid in general understanding of typical fish passage design considerations. Many of the definitions are adapted from the "NMFS Anadromous Salmonid Passage Facility Design" document (NMFS 2008b). Definitions of terms may vary among state and federal agencies, companies involved in design and construction of fish passage facilities, and across target species. These definitions are provided for use in this primer. Feel free to contact NMFS fish passage bioengineering staff with additional questions regarding terminology.

***Anadromous* –** Migratory fish species that spend much of their juvenile and adult lives in the ocean environment, returning to freshwater riverine habitats to spawn and complete their life cycle.

***Active screens* –** Fish screens targeting juvenile fish that are equipped with effective automatic debris cleaning systems that keep screens free from debris, and insure continuous maintenance of effective fish protection characteristics. Small adult fish also are protected by these screen designs.

***Approach velocity* –** The vector component of channel velocity that is perpendicular to and upstream of the vertical projection of the screen face, calculated by dividing the maximum screened flow by the *effective screen area*. An exception to this definition is for end-of-pipe cylindrical screens, where the approach velocity is calculated using the entire effective screen area. Approach velocity should be measured as close as physically possible to the boundary layer turbulence generated by the screen face.

***Apron* –** A flat, usually slightly inclined slab below a flow control structure that provides for erosion protection and produces hydraulic characteristics suitable for energy dissipation or in some cases fish exclusion.

***Attraction flow* –** The flow that emanates from a *fishway entrance* with sufficient velocity and in sufficient quantity and at an appropriate location to attract upstream migrants into the *fishway entrance*. *Attraction flow* consists of gravity flow from a *fish ladder* or *fishway* plus any *auxiliary water system* flow added at points within the lower sections of the facility.

***Auxiliary water system* –** A hydraulic system that augments *fishway* flow at various points in the *upstream passage facility.* Typically, large amounts of auxiliary water flow are added in the *fishway entrance* pool in order to increase the attraction of the *fishway entrance*.

***Backwash* –** Providing debris removal at a fish screen or fishway component by pressurized wash, opposite to the direction of flow.

***Backwater* –** A condition whereby a *hydraulic drop* is influenced or controlled by a water surface control feature located downstream of the *hydraulic drop*.

***Baffles* –** Physical structures placed in the flow path in a fishway designed to dissipate energy or to redirect flow for the purpose of achieving more uniform flow conditions. Denil fishways often have baffles made of oak.

***Bank full* –** The river or stream bank height inundated by an approximately 1.2 to 1.5 year (maximum) average recurrence interval and may be estimated by morphological features such as the following: (1) a topographic break from vertical bank to flat *floodplain*; (2) a topographic break from steep slope to gentle slope; (3) an observable change in vegetation composition; (4) a textural change of depositional sediment; (5) the elevation below which no finer debris occurs; and (6) a textural change of matrix material between cobbles or rocks.

***Bed load* –** Sand, silt, gravel, or soil and rock debris transported by moving water on or near the streambed.

***Bifurcation (or Trifurcation) pools* –** Pools where two or three sections of fishways divide into separate routes.

***Brail* –** A device that moves upward (vertically) through the water column, crowding fish into an area for collection or passage. Sometimes referred to as a "basket" in fish lock designs.

***Burst speed* –** A short-term increased swimming speed capability that enables fish to escape from predators or other fright situations.

***Bypass flow* –** In context of screen design, that portion of flow diverted that is specifically used to bypass fish back to the river.

***Bypass reach* –** An often "de-watered" riverine habitat reach below a diversion structure or dam that has diverted all or part of the river flow to another channel or hydropower canal.

***Bypass system* –** The component of a downstream passage facility that diverts water and fish around fish entrainment or impingement hazards, like hydropower turbines. System components may include a bypass entrance, transport or conveyance structure, and a safe outfall back to the river.

Catadromous **–** Migratory fish species that spend much of their juvenile and adult lives in the riverine environment, returning to the ocean to spawn and complete their life cycle. American eel are a common example of a catadromous species on the eastern U.S. seaboard.

CFD **–** Computational fluid dynamics model. Methodology to support evaluation of water flow and turbulence conditions related to fish passage facility designs at specific sites. More information on use of CFD modeling systems: http://www.cfd-online.com/

Channel bed width **–** The width of the stream or river bed under bank full channel conditions.

Conceptual design **–** An initial design concept based on site conditions and biological needs of target species intended for passage. This is also sometimes referred to as a *preliminary design*.

Crowder **–** A combination of static and/or movable *picketed* and/or solid leads installed in a *fishway* for the purpose of moving fish into a specific area for sampling, counting, brood stock collection, or other purposes.

Diadromous **–** Migratory fish that move between marine and freshwater habitats. Diadromous fish can further be separated into anadromous and catadromous.

Diffuser **–** Typically a set of horizontal or vertical bars designed to introduce flow into a *fishway* in a nearly uniform fashion. Other means are also available that may accomplish this objective.

Distribution flume **–** A fabricated channel used to route fish to various points in a fish trapping system.

Effective screen area **–** The total submerged screen area, excluding major structural members, but including the screen face material

End of pipe screens **–** Juvenile fish screening devices attached directly to the intake of a diversion pipe or industrial plant intake.

Entrainment **–** The unintended diversion of fish into an unsafe passage route.

Exclusion barrier **–** Upstream passage or diversion facilities to prevent upstream migrant fish from mistakenly entering dead end channels or harmful structures producing false attraction flows.

Exit control section **–** The upstream end of a fishway exit channel that maintains flow conditions to encourages upstream moving fish to exit the fishway.

False weir **–** An engineered device that creates a strong vertical water flow column in a fishway or river channel, to help change the direction of fish movement toward a trap or sorting pool, or to another transport channel to continue upstream passage.

Fish ladder or "fishway" **–** Facility designed with a water flow channel or chute with baffles and/or a series of pools to dissipate energy so that appropriate flow conditions can encourage fish to pass through an entrance, move up through the ladder channel, and exit above the dam or barrier.

Fish lift **–** A special mechanical fish passage system that includes a water filled hopper or basket, which lifts fish from an entrance pool below a dam up to an exit channel, passing fish to the headpond above the dam.

Fish lock **–** A mechanical and hydraulic upstream passage system that attracts fish into a lock chamber, then raises the water surface elevation to the level of the headpond or reservoir above the dam, and provides an exit for fish to continue passage upstream.

Fish passage season (upstream) **–** A seasonal range of dates encompassing the full upstream migration period of fish species, to access spawning or maturation habitats upstream from a barrier.

Fish passage season (downstream) **–** A seasonal range of dates encompassing the full downstream migration or outmigration period of juvenile and adult species, in many cases returning to the ocean.

Fishway **–** The set of facilities, structures, devices, measures, and project operations that together constitute, and are essential to the success of, an upstream or downstream fish passage system. The items which may constitute a 'fishway' under Section 18 for the safe and timely upstream and downstream passage of fish must be limited to physical structures, facilities, or devices necessary to maintain all life stages of such fish, and project operations and measures related to such structures, facilities, or devices which are necessary to ensure the effectiveness of such structures, facilities, or devices for such fish. Pub.L. 102-486, Title XVII, § 1701(b), Oct. 24, 1992.

Fishway entrance – The component of an *upstream passage facility* that discharges *attraction flow* into the *tailrace*, where upstream migrating fish enter (and flow exits) the *fishway*.

Fishway entrance pool – A component of the facility located immediately upstream from the entrance, where fishway flow and auxiliary flow is regulated to provide correct attraction for upstream migrating fish.

Fishway exit – The component of an *upstream passage facility* where flow from the *forebay* enters the *fishway*, and where fish exit into the *forebay* upstream of the passage impediment.

Fishway trap – A trap for safely capturing upstream migrating fish in or adjacent to a fish passage facility. The trap structure can be adjusted to allow free upstream passage or managed trapping for fishery management purposes.

Fishway weir – A component of "pool fishways" that controls flow between successive pools in a fishway or ladder, to encourage upstream movement of fish.

Flow duration exceedance curves – A commonly used term built upon a plot of the relationship between the magnitude of daily average flow and the percentage of time during a specified period that the flow is likely to be equaled or exceeded.

Forebay – A body of water impounded immediately upstream of a hydropower dam, containing power generating turbines and intakes (penstocks).

Freeboard – The height of a structure that extends above the maximum water surface elevation (for boats, ships, fishway exits, etc.).

Functional design – Similar to the term "*conceptual design"* included above.

Gulper – A colloquial term for a floating surface collector used as a type of downstream fish passage facility.

Head loss – A common term describing the loss of hydraulic driving energy for facilities like hydro turbines and pumps, due to various structures like fish screens, trash racks, etc.

HEC-RAS – An integrated system of software, designed for interactive use in a multi-tasking environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphical and tabular output, and reporting facilities.
More information: http://www.hec.usace.army.mil/software/hec-ras/

Hopper – A water-containing device or basket component of a lift facility that transfers fish up to the fishway exit to the body of water above a dam.

Hydraulic drop – The energy difference between and upstream and downstream water surface, which is designed to provide optimum flow conditions at a fishway entrance or exit for fish passage.

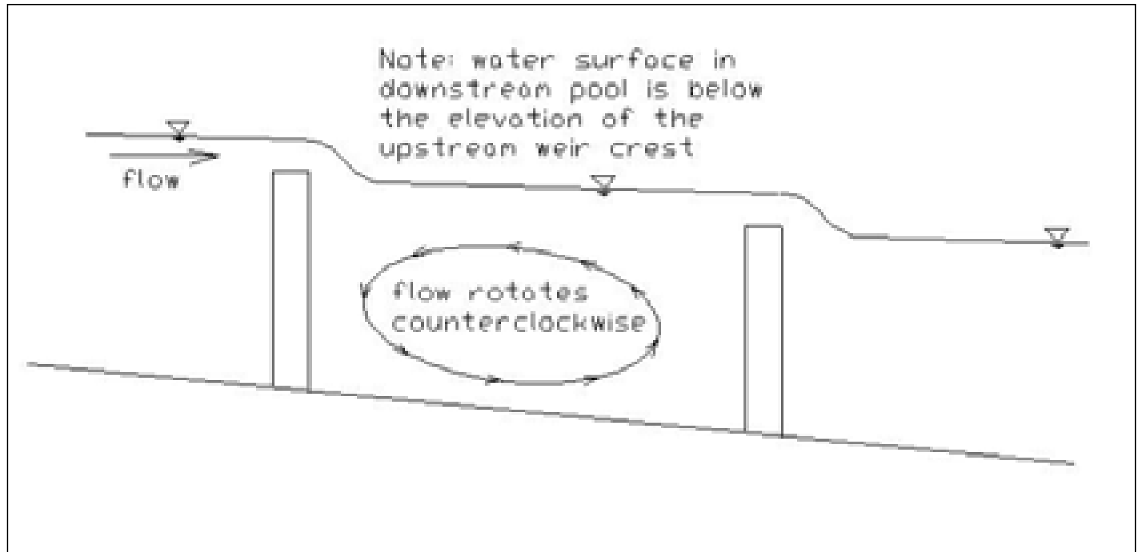
Impingement – The consequence of a situation in which flow velocity exceeds the swimming capability of a fish, creating injurious contact with a screen face or bar rack.

Passive screen – Screens designed to prevent juvenile or adult entry into an intake structure, without an automated cleaning system installed.

Picket leads or "pickets" – A series of vertically placed flat bars or circular slender columns designed to direct fish movements toward preferred passage routes through a fishway, or toward a counting window, for example.

PIT – tag detector –"Passive Integrated Transponder" implanted in fish to mark them. Often used to provide for detection of movement behavior in the riverine environment and through fishways.

Plunging flow – A common flow pattern associated with fishway weirs, when the "below weir' surface water elevation is lower than the weir crest itself. Plunging flow generally causes the downstream pool surface water movement to be upstream direction. Refer to diagram below. Nordlund (2009)



Example diagram showing plunging flow characteristics in a fishway.

Porosity – The open area of a mesh, screen, or rack relative to the entire "screen" surface area.

Positive exclusion – A means of excluding fish by providing a barrier which they cannot physically pass through.

Potamodromous – Migratory fish species whose life cycles are within fresh water only.

Preliminary design – An initial design concept based on site conditions and biological information for species intended for passage. Synonym for *conceptual design.*

Ramping Rates – Refers to regulated water flow, using increments (inches per hour, for example) to manage appropriate flow for fish passage, bypass flow alterations, etc.

Rating curve – Graphical data presentation depicting the relationship between water surface elevation and flow.

Redd – A natural fish egg deposition site or "nest" excavated in sand and gravel substrate by a spawning female salmonid.

Scour – A stream morphology term referring to streambed erosion, resulting in temporary or permanent altering or lowering of streambed profile and hydrological conditions.

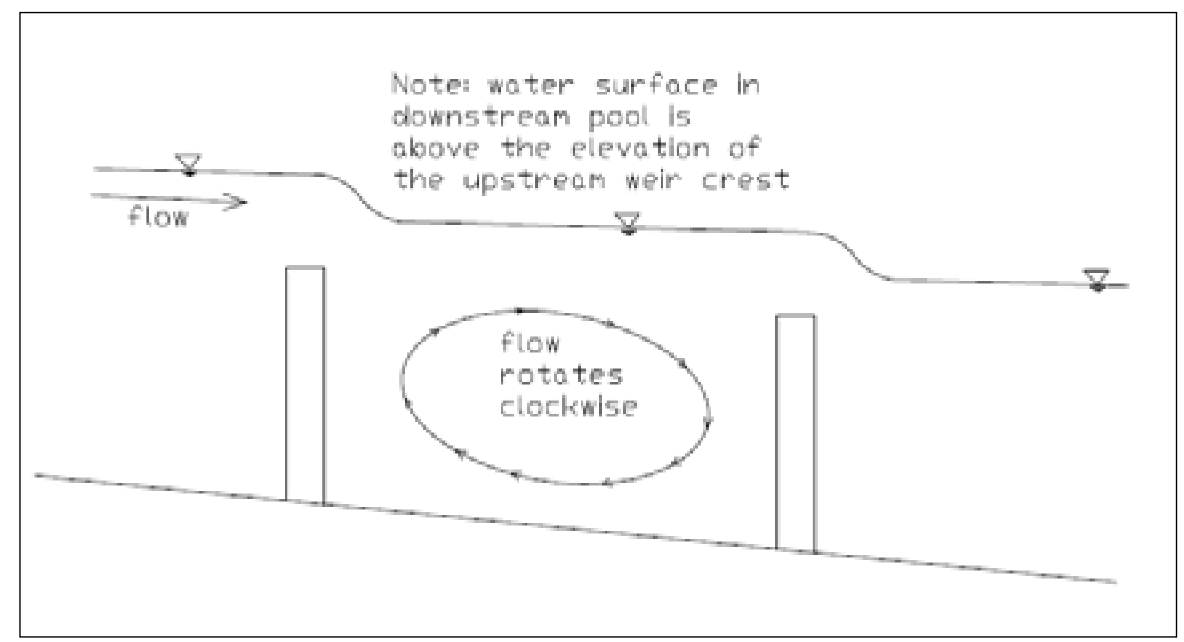
Screen material – The screen design material that provides physical exclusion to reduce the probability of entraining fish. Examples include perforated plate, bar screen, and woven wire mesh.

Smolt – A juvenile salmonid that has completed its freshwater maturation component of its life cycle, and is migrating downstream to the sea.

Smoltification – A physiological adaptation process undergone by anadromous fish fry, typically salmonids, during outmigration from freshwater to seawater. A similar salinity adaptation process may be necessary for other fry, juveniles, or adults migrating to or from seawater and freshwater environments.

Sprint Swimming Speed – A term similar to *burst speed* included above.

Streaming flow – Typically refers to flow over a fishway weir, which falls into a receiving pool with the water surface elevation above the elevation of the weir crest. This flow pattern generally results in a pool surface flow in the downstream direction. Refer to the diagram below. Nordlund (2009)



Example diagram showing streaming flow characteristics in a fishway

Sweeping velocity – Refers to the vector component of canal or river channel flow velocity that is parallel and adjacent to a fish protection screen face, measured as close as possible to the boundary layer turbulence generated by the screen face.

Tailrace – Term describing the river or water flow immediately below a dam or other barrier. Commonly refers to the area downstream from hydropower dams or power plant water discharges.

Tailwater – Refers to the larger body of water flowing below a dam.

Thalweg – The primary stream or channel flow path following the deepest parts of a river or stream channel where the highest quantity of flow is present. From German language referring to "path (weg) through a valley (thal)".

Tide gate – A gate structure located on an impoundment berm or transportation embankment culvert to regulate tidal flow. Fish passage is often associated with tide gates.

Total project head – The difference in water surface elevation from upstream to downstream of a dam or other barrier, most commonly referring to hydropower dams where this term is important for power generation.

Training wall – A physical structure designed to direct flow to a specific location or direction.

Transport channel – A hydraulic conveyance designed to pass fish between different sections of a fish passage facility.

Trap and haul – A system designed to trap and safely capture fish for upstream or downstream transport, and for collection and transport of adult brood stock to a hatchery facility. Also referred to as "trap and truck" and "trap and transport".

Trash rack – A rack of vertical bars with spacing designed to catch debris and preclude it from entering a fishway, while providing sufficient opening to all free passage of fish.

Turbine – A designed mechanical mechanism used to convert water energy to mechanical power at a mill, or generation of electrical power at a hydropower project dam.

Turbine intake screen – Partial flow screens positioned within the upper portion of turbine intakes "penstocks", designed to guide fish into a collection system for transport or bypass back to the river.

Vertical barrier screen – Vertical positioned screens usually located in a gate well of a mainstream hydro project, that dewater flow from turbine intake screens, thereby concentrating fish for passage into a *bypass system*.

Volitional passage – Fish passage designed to allow free and continuous passage by the fish's "own volition", with hydrological and channel conditions similar to an open river reach, and with no handling or forced movement.

Weir – A human-designed river obstruction over which water flows, or a structure with water flow through a series of gaps or openings.

Appendix II. Example Fish Passage and Dam Removal Projects

Atlantic and Gulf Coast River Basins

Bosher's Dam Vertical Slot Fishway

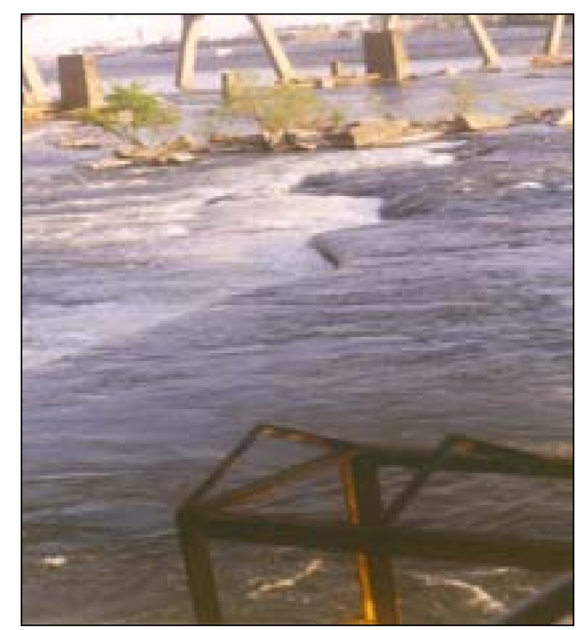
James River, Near Richmond, Virginia

Bosher's Dam was completed in 1823, and blocked over 400 kilometers of spawning habit for American shad, river herring, hickory shad, striped bass, and sturgeon. The vertical slot pool-type fishway shown below was completed in 1999, and reopened fish passage to historical spawning habitats upstream from Richmond. *Top left*: View of Bosher's Dam and Fishway. *Top right*: View of water flow through the vertical slots. *Bottom:* View downstream showing the fishway exit and bottom left, the series of pools, and the fishway entrance gates.
Photos: Alan Weaver, VADGIF.
http://www.dgif.virginia.gov/fishing/shad/boshers.html

Brown's Island and Manchester Dam Notch Project

James River, Richmond, Virginia

In 1989 the two dams were breached by explosives, each with three 25-foot breaches near the north side of the river where the channel depth is suitable for fish upstream movement and passage. The original dams were constructed in the 19th century to provide boat navigation canals through the river shoals. *Top*: Diagram showing locations of the low-head dams. *Bottom Left:* Manchester Dam breach. *Bottom Right*: Brown's Island Dam breach.
Photos: Dick Quinn, USFWS.
http://www.dgif.virginia.gov/fishing/fish-passage/#manchester-and-browns-island



Cataract Falls Fish Passage

Saco River, Maine

The Saco River is the fourth largest river basin in Maine, and the Cataract Falls Dams were the first barriers to upstream passage of ocean-river migratory fish. A settlement agreement in 1994 provided for fish passage at the Cataract and Skelton projects. Passage is provided for American shad, alewife, and blueback herring by the fish lift to nearby upstream Springs Island and Bradbury Dams. Atlantic salmon, shad, alewife, and blueback herring are collected in the fish trap facility at the fish lift, and are transported by tank trucks upstream to spawning habitats. *Top Left*: Cataract Falls East Channel fish lift. *Bottom Right*: Fish trap and transport facility on the fish lift exit channel.
Photos: Al Blott, NMFS.

Cape Fear Lock & Dam #1

Cape Fear River, North Carolina

Cape Fear Lock and Dam #1 and #2 were constructed by the U.S. Army Corps of Engineers in 1915 to 1917, and #3 was completed in 1935 to provide commercial navigation from Wilmington Harbor to Fayetteville. L&D #1 was the first blockage for anadromous fish on the Cape Fear River. Cooperation among the Corps and the fishery agencies led to operation of the locks for passage of American shad, river herring, striped bass, and other riverine species to upstream habitats. By 1994 commercial shipping traffic ceased, and lock operations for passage of anadromous fish continued. Current plans are in progress to install a "rock arch" fish passage system at the dam. *Top:* Lock & dam and steeppass fish ladder beside the lock. *Bottom:* Construction of the rock weir passage in progress by placement of rock below the dam.
Photos: Fritz Rohde, Prescott Brownell, NMFS

Cathance Stream Denil Fish Ladder

Marion Township, Maine

This standard Denil was constructed in 2000 at a natural falls on the Cathance Stream, a tributary of the Dennys River, to improve passage efficiency for Atlantic salmon during normal migration season flows.
Photos: Sean McDermott, NMFS.

Columbia Diversion Dam Vertical Slot Fishway

Broad River, Columbia, South Carolina

Columbia Diversion Dam and navigation canal and lock was constructed in 1824 to provide riverboat passage around the Columbia Shoals. In 1884, a hydroelectric power plant was built on the Columbia Canal. Marshall McDonald of the U.S. Fish Commission built a fishway at the dam in 1886 to provide passage for American shad and river herring. The fishway washed away sometime later. A new vertical slot fishway was installed and operational in 2006 designed to pass American shad, blueback herring, and other alosines. Features for safe upstream and downstream shortnose sturgeon and American eel passage were considered during design development although they were not target species.
Aerial photo: Paul Cyr, Kleinschmidt Associates; Fishway photo: Mark Cantrell, USFWS; Downstream power plant bypass entrance photo by Prescott Brownell, NMFS

Damariscotta Mill Alewife Passage

Damariscotta River, Maine

The Damariscotta Mills fish passage is located in the towns of Nobleboro and Newcastle, Maine. In1729 a double sawmill was built at the falls from Damariscotta Lake to Salt Bay at the head of the Damariscotta River estuary. The mill blocked upstream passage of alewives until 1807, when the towns constructed a fish ladder. The original ladder was dry laid stone on a seasonal overflow from the lake, and it was only marginally successful. The towns embarked on an ambitious rebuilding project in 2007. The upper 150-feet were completed in 2008, and work on 1000-feet in the middle of the fishway is ongoing. *Top left:* aerial view. *Top right:* fishway entrance. *Center row:* mid reach under construction. *Bottom row:* alewives moving upstream and example pools.
Photos: Deb Wilson, Damariscotta Mills Organization. http://damariscottamills.org/restoration.html



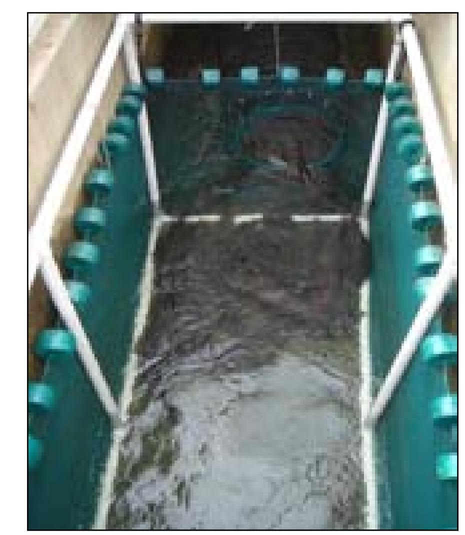



Deer Creek Denil Fish Ladder

Wilson's Mill Dam, Maryland

Wilsons Mill was built in 1810 at the site of an earlier mill in 1780 on Deer Creek, Dublin District, Hartford County, Maryland. Historically, Deer Creek supported spawning runs of American shad, white perch, yellow perch, alewife, and blueback herring. The mill dam blocked approximately 40 kilometers of spawning habitat for those anadromous fishes. A Denil fish ladder was built and re-opened historic anadromous fish spawning habitat in Deer Creek in 2000. Since the opening of the fish ladder, all of the historical species of anadromous fishes that ascended Deer Creek to spawn have been documented passing through the fish ladder.





Embry Dam Removal

Rappahannock River, Virginia

Constructed in 1910, the 22-foot high Embry Dam replaced an old 1853 timber-crib dam that caused many miles of anadromous fish spawning habitat to be lost above Fredericksburg. In 2004 the dam was breached by explosives managed by U.S. Army. Over 170 kilometers of historical spawning habitat in the Rappahannock is now open for migratory fish including American shad, blueback herring, alewife, and other species.

Photos: VADIF and NOAA.

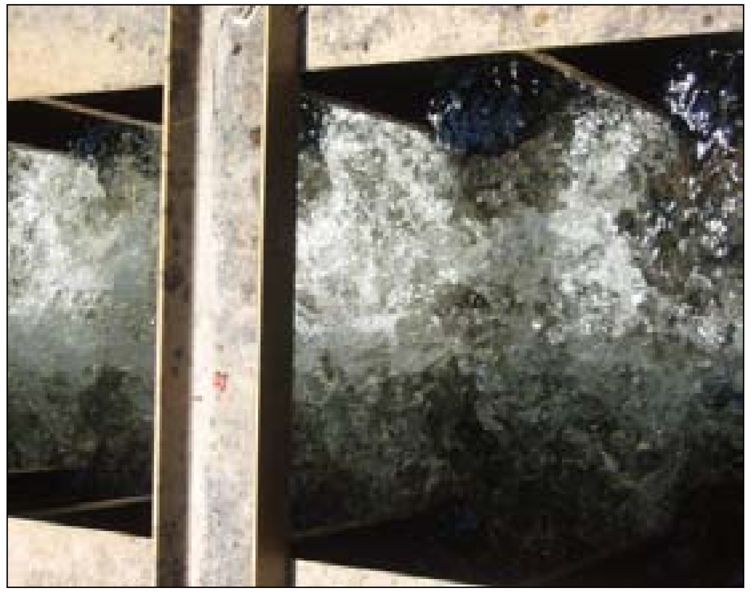
http://www.dgif.virginia.gov/fishing/embrey_dam.html

Gilbert Stuart Brook Steeppass

North Kingstown, Rhode Island

Fishway at Gilbert Stuart's birthplace (Gilbert painted portraits of George Washington). A wooden ladder was in place there for many years, until the 1960s when replaced by an aluminum steeppass design for river herring. This fishway passes thousands of river herring annually.

Photos: Al Blott, NMFS.



Greenville Project Downstream Bypass

Shetucket River, Connecticut

An example of a downstream fish bypass at the Greenville Project Dam. *Top left:* Downstream view of the bar rack fish protection structure preventing fish from entering hydropower turbines, bypass conduit entrance, and the rack cleaning rake. *Top right:* Additional length of the bar rack. *Bottom:* The bypass conduit outfall.
Photos: Al Blott, NMFS.

Heishman's Mill Dam Nature-Like Fish Bypass

Conodoguinet Creek, Susquehanna River, Pennsylvania

This nature-like fishway was one of the first in the northeast, completed in 2004-2005. Target species for passage include American shad, river herring, and riverine species. Heishmans Mill Dam was constructed around 1834. *Top left:* Bypass entrance. *Top right:* Bypass exit. *Bottom left:* Exit water control structure. *Bottom right:* view of channel.
Photos: Scott Carney, PAFBC.

Homestead Woolen Mill Dam Removal/Nature-like Fishway

Asheulot River, West Swanzey, New Hampshire

The timber-crib dam was removed in 2010, and three cross vane rock structures installed to prevent upstream downcutting to protect the 1832 Thompson Covered Bridge. Passage is restored to over 40 kilometers of riverine habitat for American shad, river herring, sea lamprey, American eel, and Atlantic salmon in the Asheulot River, tributary of the Connecticut River.
Photos: Jim Turek, NMFS
http://www.ctriver.org/programs/restoration/current_projects/index.html

Mill River Culvert Passage

Westbrook, Maine

Pool and weir fishway installed in 2005, to provide passage at perched culverts that restricts passage at normal and low water conditions. Passage is provided for alewife, blueback herring, and possibly American eel in the future.
Photos: Sean McDermott, NMFS

Octoraro Dam Removal

Octoraro Creek, Susquehanna River, Maryland

The dam was constructed in the 19th century and blocked upstream passage of American shad and river herring for over 100 years. Removal was completed in October 2005 to restore fish passage to over 30 kilometers of important spawning habitat, and to provide recreational canoeing access. The Maryland DNR Fish Passage Program and U.S. Fish and Wildlife Service, and other partners initiated the dam removal planning process.
Photos: Maryland DNR, and Jim Turek, NOAA.
http://www.dnr.state.md.us/fisheries/fishpassage/octoraro111605.html

Parker River Alaska Steeppass Fish Ladder

Newbury, Massachusetts

An Alaska steeppass was constructed on the Parker River in 2001. Target species for passage were alewife and blueback herring.
Photos: Sean McDermott, NMFS.

Phippsburg Denil Fish Ladder

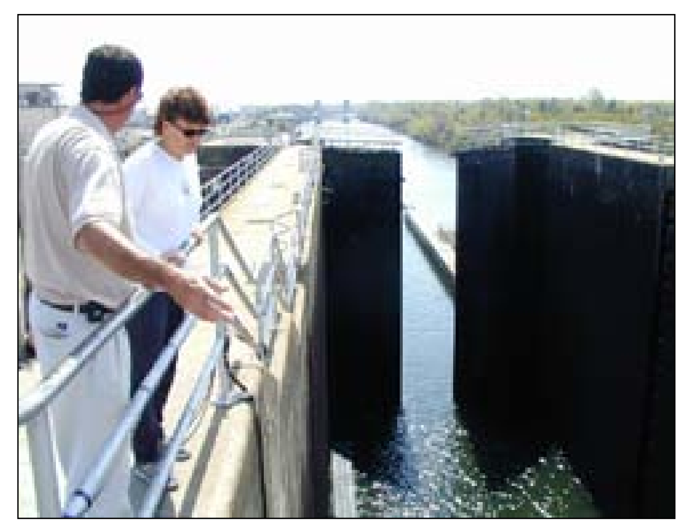
Center Pond, Kennebec River, Phippsburg, Maine

An intertidal Denil at Center Pond adjacent to the tidal reach of the Kennebec River. View shown below is at low tide. Rebuilt in 2004. Target species for passage include alewife, blueback herring, and American eel.
Photos: Sean McDermott, NMFS.

Pinopolis Dam and Navigation Lock

Cooper River, Santee Diversion Project, South Carolina

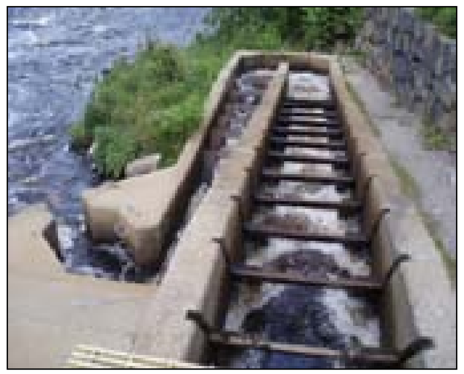
Pinopolis Dam and Lock was constructed in 1938 to 1942 as a component of the Santee Diversion Project, diverting the Santee River into the small coastal Cooper River to Charleston Harbor. Lock passage for striped bass, blueback herring, and American shad began in 1944, when large schools of fish gathered below the lock and dam after the river diversion. Millions of herring and shad have passed upstream through the lock annually.
Photos: Aerial view, Mark Cantrell, USFWS; lock operation, and original 1970s sonar fish counter, Prescott Brownell, NMFS.



Potter Hill Mill Dam Denil Fishway

Pawcatuck River, Hopkinton, Rhode Island

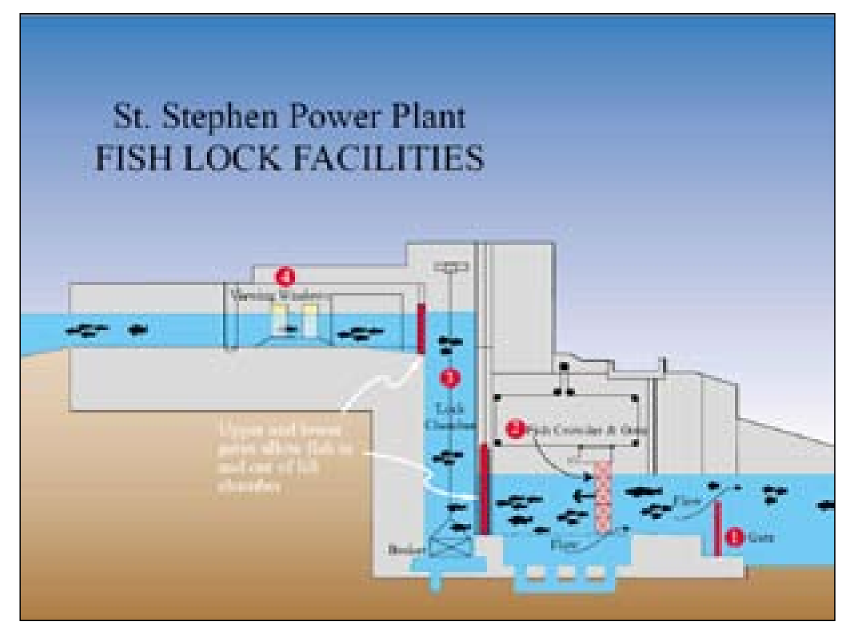
The Potter Hill Dam was built in 1762 to power textile mills. The mills ceased operating in 1958, and one mill building burned in 1978. The 10-foot high dam was renovated in1941, and the Denil fishway, which opened up about 12 kilometers, was constructed in 1973. Relatively higher flows shown opposite from the fishway reduce attraction of anadromous species to the fishway. Planned dam removal and construction of fishways at two upstream obstructions will complete the restoration of one of the largest watersheds in Rhode Island.
Photos: Al Blott, NMFS.



St. Stephen Fish Lock

Santee River, South Carolina

The St. Stephen Fish Lock (usually called Fish Lift) was constructed in 1981 to 1985 as a component of the Cooper River Rediversion Project by the U.S. Army Corps of Engineers. It is located on the Rediversion Canal between Lake Moultrie and the Santee River. Operation for fish passage began in 1986, for target ocean-river migratory fish including American shad, blueback herring, and other alosines. Hundreds of thousands of blueback herring and American shad are passed upstream annually. St. Stephen Powerhouse is shown below with the Fish Lock entrance and exit shown on the right side of the canal. A diagram showing features of the Fish Lock is also shown below.
Photos: USACE, Mark Cantrell, USFWS
http://www.youtube.com/watch?v=emgN59IFMIE



Sawmill Dam Nature-like Fishway

Acushnet River, Massachusetts

The Sawmill Dam was located 1000 feet upstream from New Bedford Harbor on the Acushnet River. In 2008, the dam was notched on the river right side and a step-pool design or "rock arch" nature-like fishway was constructed to provide normal passage for river herring. The nature-like fishway restored passage to over 5 kilometers of important spawning habitat.

Photos: Jack Terril and Jim Turek, NMFS.

Sebasticook Pond Fishway

Sebasticook River, Newport, Maine

This pool and chute fishway was constructed in 2003 to restore passage for river herring, Atlantic salmon, and American eel into Sebasticook Pond. This project provides access to target spawning and rearing habitat in the upper reaches of the Sebasticook River.

Photos: Sean McDermott, NMFS

Sennebec Pond Rock Ramp

St. George River, Union, Maine

A rock ramp fishway at the natural outlet of Sennebec Pond was constructed allow passage of all resident and diadromous fish species while maintaining the pond at its current level. Following construction of the rock ramp, Sennebec Dam, the only substantial obstacle to fish passage in the St. George watershed, was removed. This effort restored 2000 feet of impounded river to its natural condition, opened 17 miles of the mainstem St. George for Atlantic salmon, blueback herring, eel, and shad, and 1100 acres of lake habit in Sennebec Pond and Quantabacook Lake for alewife.

Photos: Eric Hutchins, NMFS

Somes Pond Pool and Weir Fishways

Somes Sound Watershed, Mount Desert Island, Somesville, Maine

Two pool and weir fishways: one under construction, one in operation. Both on the Somes Pond outlet stream to Somes Sound. Historically more than two hundred thousand adult sea-run alewives ascended to Somes Pond and Long Pond each year. Target species for passage include alewife, sea lamprey, and American eel.

Photos: Sean McDermott, NMFS; Sandra Lary, USFWS

http://www.fws.gov/northeast/gulfofmaine/news/somesville.htm

Steele's Mill Dam Removal

Hitchcock Creek, Pee Dee River, Cordova, North Carolina

Steele's Mill Dam, a cotton mill, and mill village to accommodate Irish immigrants were constructed in the 1880s near the Town of Rockingham. The mill was later converted from hydromechanical power to hydroelectric power, and continued operation until 1999. The dam was removed in 2008 in collaboration with the Town of Rockingham, American Rivers, N.C. Wildlife Resources Commission, U.S. Fish and Wildlife Service, NOAA Restoration Center, and NMFS.

Photos: Howard Schnabolk, Fritz Rohde, Prescott Brownell, NMFS.

Williams Island Dam Notch

James River, Richmond, Virginia

The City of Richmond draws its drinking water from the pool behind the dams at William's Island on the James River in Richmond. The most upstream dam on the south channel is most commonly known as the Z-Dam. In November of 1993 a 30-foot wide by 2.5-foot deep notch was cut into the dam to allow migratory fish passage. This was a cooperative effort of the VDGIF, the City of Richmond, the James River Association, the EPA Chesapeake Bay Program, NMFS, and the USFWS.

Photo: Dick Quinn, USFWS.

West Winterport Dam Removal

Marsh Stream, Winterport, Maine

Attached are before and after pictures of the West Winterport dam removal on Marsh Stream, near the towns of Winterport and Frankfort, Maine. The old hydropower dam was removed in August 2010, reopening over 135 kilometers of spawning habitat for sea-run fish including Atlantic salmon, shad, and river herring.
Photos: John Jones, dam owner; Al Blott, NMFS.

http://new.bangordailynews.com/2010/0929/975doors/winterport-dam-removal-elebrated/#

Jim Woodruff Lock & Dam

Apalachicola River, Florida and Georgia

The lock and dam was authorized by Congress in 1946, and construction was completed in 1952. The dam blocked historical sea-run migratory fish spawning runs to the Flint and Chattahoochee rivers and many tributaries in the Apalachicola-Chattahoochee-Flint watershed. Important migratory fish include Gulf sturgeon, striped bass, Alabama shad, and American eel. Active upstream passage began for shad at the lock in the late 1990s through collaboration with the U.S. Army Corps of Engineers, state fishery agencies in Florida, Georgia, and Alabama, The Nature Conservancy, U.S. Fish and Wildlife Service, and National Marine Fisheries Service. Over 100,000 Alabama shad were passed upstream in 2010.
Photo: USACE