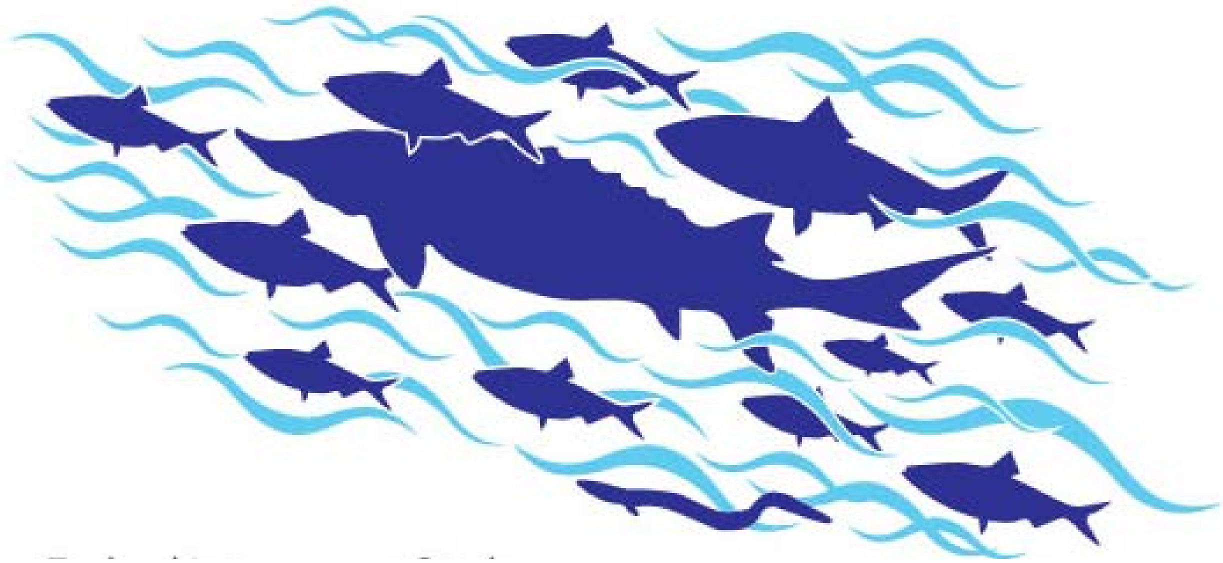
Technical Memorandum

Federal Interagency Nature-like Fishway Passage Design Guidelines for Atlantic Coast Diadromous Fishes



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DEPARTMENT OF THE INTERIOR

Technical Memorandum
Federal Interagency Nature-like Fishway Passage Design Guidelines for Atlantic Coast Diadromous Fishes

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Abstract: The National Marine Fisheries Service (NMFS), the U.S. Geological Survey (USGS) and the U.S. Fish and Wildlife Service (USFWS) have collaborated to develop passage design guidance for use by engineers and other restoration practitioners considering and designing nature-like fishways (NLFs). The primary purpose of these guidelines is to provide a summary of existing fish swimming and leaping performance data and the best available scientific information on safe, timely and effective passage for 14 diadromous fish species using Atlantic Coast rivers and streams. These guidelines apply to passage sites where complete barrier removal is not possible. This technical memorandum presents seven key physical design parameters based on the biometrics and swimming mode and performance of each target fishes for application in the design of NLFs addressing passage of a species or an assemblage of these species. The passage parameters include six dimensional guidelines recommended for minimum weir opening width and depth, minimum pool length, width and depth, and maximum channel slope, along with a maximum flow velocity guideline for each species. While these guidelines are targeted for the design of step-pool NLFs, the information may also have application in the design of other NLF types being considered at passage restoration sites and grade control necessary for infrastructure protection upstream of some dam removals, and in considering passage performance at sites such as natural bedrock features.

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Disclaimer: The efficacy of any fish passage structure, device, facility, operation or measure is highly dependent on local hydrology, target species and life history stage, barrier orientation, and a myriad of other site-specific considerations. The information provided herein should be regarded as generic guidance for the design of NLFs for the Atlantic Coast of the U.S. The guidelines described are not universally applicable and should not replace site-specific recommendations, limitations, or protocols. This document provides generic guidance only and is not intended as an alternative to proactive consultation with any regulatory authorities. The use of these guidelines is not required by NMFS, USFWS or USGS, and their application does not necessarily imply approval by the agencies of any site-specific design.

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Acknowledgements

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Introduction

Diadromous fishes spend portions of their lives in marine, estuarine and freshwater environments and migrate great distances throughout their life cycles. All diadromous fish species require unimpeded access between their rearing and spawning habitats. Diadromous fishes that use freshwater rivers and streams of the Atlantic Coast of the U.S. as spawning habitats include a diverse anadromous species assemblage, and the catadromous American eel (*Anguilla rostrata*) which spends much of its life in freshwater rearing habitat with adults out-migrating to spawn in the Sargasso Sea. These fishes deliver important ecosystem functions and services by serving as forage for higher trophic-level species in both marine and freshwater food webs (Collette and Klein-MacPhee 2002; Ames 2004; McDermott et al. 2015) and providing an alternative prey resource (i.e., prey buffer benefitting other species) to predators in estuaries and the ocean (Saunders et al. 2006). In rivers and streams, services provided by this diadromous fish assemblage include relaying energy and nutrients from the marine environment (Guyette et al. 2013),transferring energy within intra-species life stages in streams (Weaver 2016), providing benthic habitat nutrient conditioning and beneficial habitat modification (Brown 1995; Nislow and Kynard 2009; West et al. 2010), serving as hosts to disperse and sustain populations of freshwater mussel species (Freeman et al. 2003; Nedeau 2008), and enhancing stream macro-invertebrate habitat (Hogg et al. 2014).

Diadromous fishes are also recognized in contributing significant societal values. Historically, Native Americans, European colonists, and post-settlement America relied heavily on these species as sources of food and for other uses (McPhee 2003). Many of these diadromous fish species are highly valued in supporting commercial and recreational fisheries, with some species prized as sportfish and/or food sources including culinary delicacies (Greenberg 2010). They also contribute to important passive recreational opportunities where people can observe spring fish runs, learn about their life histories, and appreciate these migratory fishes and their key roles in riverine, estuarine and marine ecosystems (Watts 2012).

Many populations of Atlantic Coast diadromous fishes have been in serious decline for decades due to multiple factors including hydro-electric dams and other river barriers preventing access to spawning and rearing habitats, water and sediment quality degradation, overharvesting, parasitic infestations and other fish health effects, body injuries due to boat strikes and other human-induced impacts (Limburg and Waldman 2009; Hall et al. 2011; Waldman 2014). Shortnose sturgeon (*Acipenser brevirostrum*), Atlantic salmon (*Salmo salar*), and Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) (NMFS 1998, 2009, 2013a) have been designated as endangered under the Endangered Species Act (ESA) (Atlantic sturgeon are currently listed as threatened in the Gulf of Maine). American eel were recently considered for listing under the ESA (USFWS 2011, 2015) and are currently designated as a Species of Concern. Both alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*) were designated as Species of Concern in 2006 (NMFS 2006), and NMFS was petitioned in 2011 to list both as ESA species. NMFS completed its review for the candidate ESA listing in 2013 and determined that listing either river herring species was not warranted as either threatened or endangered. NMFS continues to collect and assess monitoring data on the status of populations and abundance trends of and threats to each river herring species (NMFS 2013b). Rainbow smelt (*Osmerus mordax*) were also previously designated by NMFS as a Species of Concern (NMFS 2007).

To address these precipitously declining diadromous fish populations, pro-active restoration has been implemented by many agencies and non-governmental organizations to help restore diadromous fish runs by removing dams and other barriers, installing technical and nature-like fishways, or a combination of these passage restoration alternatives (NOAA Fisheries 2009, 2012; Schrack et al. 2012). Improving habitat access through dam removal and other measures may also contribute to diadromous species recolonizing historic freshwater habitats and increasing abundance and distribution of target species locally (Pess et al. 2014). Federal regulatory programs also seek to minimize upstream and downstream mortality of diadromous fishes passing hydro-electric dams or other river and stream barriers by requiring mitigative passage measures (e.g., ASMFC 2008, 2010; NOAA Fisheries 2012, 2015).

The NMFS and USFWS have well-established programs to address diadromous restoration by providing funds for and/or technical assistance in the planning, design and implementation of fish passage restoration (See NOAA site: http://www.habitat.noaa.gov/restoration/approaches/fishpassage.html; and USFWS site: https://www.fws.gov/northeast/fisheries). Both NMFS and USFWS along with USGS seek to advance engineering design and technology in providing safe (from both physical injury and predator avoidance), timely, and effective upstream and downstream passage for all diadromous species targeted for restoration. At many passage barrier sites, complete removal of the obstruction presents the best alternative for restoring diadromous fish passage and watershed populations (ASMFC, 2009; Martin and Aspe 2011; NOAA Fisheries 2012).

For sites where barriers cannot be fully removed or modified, other passage alternatives can be considered. Nature-like fishways (NLFs) include a wide variety of designs such as step-pools, roughened ramps, rock-arch rapids, rocky riffles, and cross vanes which are typically constructed of boulders, cobble, and other natural materials to create diverse physical and hydraulic conditions providing efficient passage to multiple species including migratory and resident fish assemblages. NLFs also provide greater surface roughness and flow complexity than typical technical (or structural) fishways (e.g., Denil, steep-pass fishways), creating attractive flow cues to passing fish. Interstitial spaces and surface irregularities associated with NLFs also provide cover and spawning microhabitats, which may be particularly important in watersheds where these specific habitats are limited. The use of natural materials in NLFs such as fieldstone boulders and cobble is also beneficial in lessening the likelihood of fish injury from sharp-edge structures such as those typically associated with structural fishways. NLF designs such as partial or full-river width or bypass channels around barriers can result in effective passage if appropriately designed and constructed for passing fish over a wide range of flows throughout the anticipated seasonal run period for a target species or run periods for targeted fish species assemblage.

Rationale for Passage Guidelines

Fish passage guidelines contribute to best design practices, promote design consistency, and facilitate time and cost-efficiency and quality in engineering design of NLFs and related passage supporting ecological restoration of river systems. NMFS, USGS and USFWS initiated a collaborative effort in 2010 to compile and review existing information from published journals, reports and other unpublished literature on body dimensions and the swimming and leaping capabilities of 14 Atlantic Coast diadromous fish species, and passage and hydraulic functioning of existing fishways. Published data on critical swim speed for each species were also secured, when available. NMFS also organized and held a technical workshop including fish passage biologists and engineers from USGS, USFWS, NMFS and state agencies experienced with diadromous fish passage in the Northeast region to discuss knowledge and experiences in species passage success and challenges (NMFS, Gloucester, MA; February 11, 2010). Subsequent federal agency meetings were held and follow-up consultations were made with professionals from state agencies, academia, and private industry to secure supplemental information on the biology of these target species and their experience with and data available for or analysis of fish swimming performance and/or passage evaluation of the Atlantic Coast diadromous fish species.

Compiling and assessing species data and information from experts with knowledge of the species and field and flume laboratory experiences, NMFS, USGS and USFWS applied the collective dataset in developing science-based guidelines when fish swimming and leaping data were available, or best professional judgment when scientific data were limited or unavailable. Best professional judgment is defined herein as personal observations and/or unpublished data provided by experienced fishery professionals knowledgeable of the swimming and leaping capabilities and behaviors of one or more of the target species.

Compiled information includes the ranges in body length and depth for each of the 14 target diadromous species, to derive body depth-to-total length ratios. These data were then applied in developing a set of six dimensional guidelines for designing passage openings and resting pools. To date, swim speed data from controlled respirometer experiments are available for 10 of the 14 species. Swim data from controlled open-channel swimming flume experiments were available for 8 of the 14 species (data for shortnose sturgeon and Atlantic salmon from USGS Conte Laboratory open flume are forthcoming). Swimming performance data from both respirometer and open-channel swimming flume research was then used to derive maximum through-weir velocity guidelines for each species. Where performance data for a species are minimal, more conservative estimates have been applied in developing the guidelines. The rationales for the guidelines presented in this document include published references or other source of information, as indicated; otherwise, guidelines presented herein are based on best professional judgment.

These guidelines are primarily for purposes of informing the design of NLFs, and in particular, nature-like, step-pool fishways that include resting pools formed by boulder weirs with passage notches specifically designed for the intended target species. One or more of these passage guidelines may also have application to other types of NLFs. These guidelines may also be considered for application in evaluating potential passage alternatives at low-head dams and other barrier sites (e.g., flow diversion and gauging station weirs) and in designing grade control structures upstream of potential dam removals to improve fish passage and/or to protect upstream infrastructure (e.g., bridges and utilities buried in channel bed and bordering floodplain). At some dam removal sites, passage design features may be required upstream of barrier removals to take into account channel bed adjustments which may otherwise result in exposure of and damage to existing infrastructure and/or re-exposure of natural bedrock features. These guidelines may also have application for assessing the likelihood of safe, timely and effective passage at existing natural barriers considered in the context of passage restoration throughout a watershed. As additional studies on fish swimming performance and fish passage effectiveness are completed, these guidelines may be subject to further updates and revisions.

Existing Fish Passage Design Criteria and Guidance

During development of these guidelines, a thorough review was conducted to evaluate other efforts in establishing criteria for fish passage design. To date, a science-based application of fish body morphology, swimming and leaping capabilities, and behavior for passage design has been limited, with most early studies and publications focused on salmonid passage through culverts in the U.S. Pacific Northwest (as summarized in Orsborn 1987). Bell (1991) presents a synopsis of biological requirements of a limited number of fish species which are then applied to developing biological design guidance including swimming speeds of both juvenile and adult life stages; the published swimming speeds are based primarily on limited and non-standardized experimental methods. Clay (1995) provides an overview of fishway types and examples of installed technical fishways on the Atlantic Coast of North America and elsewhere, with passage guidance that targets hydraulics over weirs, through slots or orifices, and in resting pools which are related to varying fish swims speeds. Beach (1984) and Pavlov (1989) note that body length and water temperature influence swim speeds which in turn help to define passage design guidance.

The Food and Agriculture Organization (FAO 2002) released guidance on European upstream fish passage design, as a follow-up to a 1996 publication prepared by the German Association for Water Resources and Land Improvement (‘DVWK’). The FAO document addresses general fish body size and swim speed of a number of European species, along with designated river “fish zones” in which diadromous and resident fishes are found. The FAO guidance also addresses both nature-like and technical fishways, and general design and detailed guidelines for, and completed examples of (e.g., design dimensions, construction materials and fishway sizes) nature-like fishways. The FAO document is the first guidance for nature-like fishway design, taking into account the swimming and leaping capabilities of fishes.

The Maine DOT (2008) presents both a fish passage policy and design guidelines for passage of diadromous and freshwater fishes through culverts including a minimum-depth guideline applied to low flows, and a maximum-flow velocity guideline based primarily on body-length derived from sustained swimming speeds of target species. The Maine DOT guidance does not address design guidance for fishways. Similar culvert design guidance was released by the Vermont DFW (2009) discussing Atlantic salmon and resident freshwater species biometric and swimming information for passage design including maximum jump height, and a minimum passage water depth of 1.5 times the maximum body depth of the target species. Other states (Washington, California) have released guidance materials for anadromous fish passage design of culverts (Bates et al. 2003, California Department of Fish and Game 2009). The guidelines for velocity and jump height thresholds in these design documents are typically intended to provide passage conditions for the weakest fishes and smallest individuals of each species, while the minimum passage depth guideline for a species is based on the largest-sized fish expected to pass.

There are several sources of passage design for the construction of nature-like fishways. NMFS' Northwest Region provides guidance for passage specifically for Pacific salmonids (primarily genus *Oncorhynchus*) (NMFS 2008, updated 2011), with fish biological requirements and specific design guidelines (prescriptive unless site-specific, biological rationale is provided and accepted by NMFS) and general guidelines (specific values or range in values that may vary when site-specific conditions are taken into consideration) to address a variety of passage types including both technical fishways and nature-like ramps. Aadland (2010) addresses dam removal and nature-like structures for achieving fish passage targeting Mid-Western region warm and cool water fish assemblages, with nature-like fishways serving as features to emulate natural rapids and providing a range of passage conditions and in-fishway habitats benefitting diverse fish assemblages with varying species' swimming capabilities. The document also presents a review of engineering design practices for rock ramp, rock arch rapids and bypass channels. The U.S. Department of Interior's Bureau of Reclamation (Mooney et al. 2007) provides detailed guidelines for nature-like rock ramp design, although species-specific body metrics and swimming and leaping requirements are not addressed in detail.

This existing published passage guidance literature contributes valuable input on how criteria and guidelines have been developed for a number of fish species and variety of fish assemblages and river systems. Conversely, none of the guidelines are targeted specifically for Atlantic Coast diadromous fishes which each have specific body morphology and swimming and leaping capabilities. NMFS, USGS and USFWS thus seek to provide a set of guidelines addressing this diadromous fish assemblage for use by passage restoration practitioners.

Federal Interagency Guidance with Science-Based Application

As noted above, the federal interagency team reviewed and evaluated relevant published journal articles, reports and gray literature, summarized and selected more recent data gained through controlled experiments (e.g., USGS Conte Anadromous Fish Laboratory and other open channel flumes), utilized past performance data from constructed NLFs (primarily in the Northeast), and advanced hydraulic formulae pertinent to nature-like fishway design (e.g., SMath model; See Towler et al. 2014) to develop these science-based guidelines. These guidelines are intended to benefit passage design professionals with information to provide safe, timely and effective passage for Atlantic Coast diadromous fish species targeted in using step-pool and other NLFs.

Target Species

Biological information has been compiled and evaluated for fourteen diadromous species in developing these passage design guidelines. The species addressed in this memorandum include species endemic to the Atlantic Coast. The species are listed according to an evolutionary taxonomic hierarchy (**Table 1**). While not currently addressed by this document, other anadromous (e.g., sticklebacks), amphidromous, and/or potamodromous fish species may be added in future interagency updates, as more research-based swimming and leaping performance data become available and are evaluated.

Table 1. Atlantic Coast Diadromous Fish Species, Common and Scientific Names

Common Name	Scientific Name
Sea lamprey	*Petromyzon marinus*
Shortnose sturgeon	*Acipenser brevirostrum*
Atlantic sturgeon	*Acipenser oxyrinchus oxyrinchus*
American eel	*Anguilla rostrata*
Blueback herring	*Alosa aestivalis*
Alewife	*Alosa pseudoharengus*
Hickory shad	*Alosa mediocris*
American shad	*Alosa sapidissima*
Gizzard shad	*Dorosoma cepedianum*
Rainbow smelt	*Osmerus mordax*
Atlantic salmon	*Salmo salar*
Sea-run brook trout	*Salvelinus fontinalis*
Atlantic tom cod	*Microgadus tomcod*
Striped bass	*Morone saxatilis*

The species diversity and abundance of a species within a watershed targeted for restoration depends on the river size or stream order, although other factors, particularly the number and location of passage barriers in a watershed will influence passage restoration planning. Fish passage engineers and other practitioners should consult with fishery biologists familiar with existing diadromous fish populations and historic run data on a regional basis and with the watershed targeted for restoration to secure reliable species and meta-population-specific information on run timing and projected restored run size for each targeted species. Information should include the range of earliest to latest dates of passage, including documented or anticipated earlier season runs or truncated run periods due to climatic change effects on in-stream water temperatures and/or peak discharges. The identification and agreement on the target species to be restored in a watershed and passed at a proposed restoration site should be a principal project objective and central to the initial step in the design process (See Palmer et al. 2005).

Run Timing and Passage Flows

Seasonal timing of fish migrations is a key consideration in fishway design, and needs to be thoroughly considered in determining fish passage design flows and fishway discharge. Fish run timing is often highly variable throughout each species' geographical range, between watersheds, and over years. Run timing, encompassing the beginning, peak, and end of a fish species migratory run period (or spring and fall run periods), is influenced by multiple factors. These factors include genetics; environmental conditions such as precipitation and other weather events and patterns; freshwater, estuarine or oceanic conditions; river flows including the effects of hydro-electric impoundment releases or water withdrawals; in-stream turbidity, dissolved oxygen levels and water temperatures including short-term fluctuations in air and water temperatures; time of day and ambient light conditions; and the specific passage site location within a watershed. Changes in the timing (along with changes in species range and recruitment and habitat change due to sea-level rise) of Atlantic Coast migratory fish runs due to climate change have been identified in a number of locations (Huntington et al. 2003; Juanes et al. 2004; Fried and Schultz 2006; Ellis and Vokoun 2009; Wood and Austin 2009).

For purposes of this document, the federal agency team recommends that a NLF be designed to function in providing passable conditions over a range of flows from the 95% to 5% flow exceedance during the targeted species migratory run period or the collective run periods for multiple target species. The range of river flows used to inform the design of a fishway can be graphically represented by a flow duration curve (FDC). The FDC should be based on the historic probability of flows at the site, or scaled to the project site from an appropriately similar reference site. Active, continuously operated USGS stream gages typically provide the most reliable and complete record of flows for rivers and streams in the U.S. (More than 8,500 flow gages are currently operated by USGS, nationwide; http://waterdata.usgs.gov/usa/nwis/rt). To reasonably estimate future conditions, a sufficiently long period of record (POR) is required. In general, a POR of 10 to 30 years is recommended. Furthermore, the use of post-1970 flow data is preferred to account for documented increasing peak flows over time due to climatic change (See Collins 2009). Additional considerations that influence the length of the POR may include, but are not limited to, gauge data availability, alterations in upstream water management, and changing trends in watershed hydrology.

Body Morphology, Swimming and Leaping Capabilities and Behaviors

Diadromous fishes vary greatly in body shape and size and swimming and leaping capabilities. General body size in fish populations may be affected by genetics, environmental conditions and other factors. Historic fishery catch data indicate decreasing trends in average body size of anadromous fishes that have resulted from overharvesting and natural mortality factors (ASMFC 2012; Waldman 2014; Waldman et al. 2016). Fish body shape and anatomy are determinants of how a fish moves, functions, and adapts to its river environment. Fish body size also affects swimming performance, and swimming ability is largely a function of fish biomechanics and hydrodynamics of its environment (Castro-Santos and Haro 2010). Larger fish have proportionally more propulsive area and a larger muscle mass, and are thus able to move at greater absolute speeds (i.e., the absolute distance through water covered over time). For example, a 10-cm long striped bass swimming at 5 body lengths per second will move through the water at 50 cm per second, while a 50 cm striped bass swimming at 5 body lengths per second will move through the water at 250 cm per second. Larger fish may also have a greater likelihood of injury from coming in contact with boulders or other structures. Fish age, physiological state, and environmental conditions such as water temperature, are additional factors influencing fish movement, behavior (e.g., propensity to pass in schools or groups), passage efficiency, and ultimately passage effectiveness.

In addition to swimming biomechanics, fish exhibit an equally important variety of behavioral responses to their physical and hydraulic environment such as motivation, attraction, avoidance, orientation, maneuvering, station-holding, depth selection, and schooling. In particular, schooling behavior occurs with some species and should be accommodated in fish passage design (e.g., passage opening dimensions and/or multiple openings within each boulder weir). Although basic behaviors of fish have been studied in both laboratory and field environments, only a modest number of behavioral studies have directly addressed fish passage. Most behavioral observations in reference to passageways have been a secondary outcome of passage evaluation studies, where study objectives or experimental designs were not focused on the evaluation of the causes of the behavioral responses.

Understanding the swimming capability of a target species is critical to designing fish passage sites. Swimming performance depends greatly on the relationship between swim speed and fatigue time. At slower speeds, fish can theoretically swim indefinitely using aerobic musculature. Once swim speed exceeds a certain threshold, fish begin to recruit different muscle fibers that function without using oxygen. This condition is noticeable by the onset of *burst-and-coast swimming* – a kinematic shift, whereby fish use both aerobic and anaerobic muscle fibers to power locomotion (Beamish 1978). Anaerobic muscle fibers can only perform for brief periods before running out of metabolic fuel; thus, high-speed swimming results in fatigue and is usually of very short duration. This physiological condition affects potential passage by a fish through high-velocity zones in rivers and fishways. In general, fish swim at speeds requiring anaerobic metabolism infrequently, given the energetic demands of this swimming mode.

Three operationally-defined swimming modes exist in fish: sustained, prolonged, and sprint speeds. Sustained swimming occurs at low or sustained speeds that are maintained for greater than 200 minutes (Beamish 1978). Prolonged swimming occurs at speeds that fish can maintain for 20 seconds to 200 minutes, and sprint swimming can only be maintained for periods of less than 20 seconds. Determining these swim modes and the critical swim speed – the threshold at which a fish changes from sustained to prolonged swim speeds (U_{crit}) is challenging. For many species, quantitative measures of these swimming modes are unknown, and only a few fish species have been comprehensively evaluated for all three modes.

Laboratory respirometer experiments are used to determine the thresholds for a species' swim speeds, but these tests tend to underestimate maximum swimming speed, and may therefore, be limited in accurately measuring burst-speed swimming. Determining burst swimming speeds is usually conducted in open channel flumes, but these experiments can also be biased by fish behavior, stress, or motivation (Webb 2006). Nonetheless, open channel flume studies usually provide better estimates of true swimming performance than results from studies of fish in respirometers, and are the preferred data source for determining fish swimming capabilities and for establishing the passage guidelines presented in this document (Castro-Santos and Haro 2006). Existing experimental swim data are also limited in terms of the size range of fish, species life history stage, and experimental water temperatures (Castro-Santos and Haro 2010). Swimming capabilities of fish may also be significantly influenced by turbulence, air entrainment, or other hydraulic/physical factors that influence swimming efficiency and fish motivation (Webb et al. 2010).

Leaping (or "jumping") is another component of swimming performance that must be considered in designing and assessing fish passage sites. Leaping height is positively correlated with swimming speed and water depth of the pool from which fish leap. Larger or deeper pools allow higher swimming velocities (i.e., a "running start") to be attained before leaping. Larger fish tend to have greater absolute leaping heights, but also require corresponding increased depths from which to leap. Leaping behavior can be initiated by the fall or plunging flow into a pool creating strong submerged water jets which serve as a stimulus and orientation cue for the direction and speed of an ensuing leap. While salmonids are known to leap during their upstream passage, many non-salmonid fish species are poor leapers or do not leap at all, being physically restricted by body morphology or maximum swimming speed, or more commonly, being behaviorally reluctant to do so. Leaping increases the potential risk of injury or stranding. Typically, leaping or sprint swimming behavior are expressed only when other behaviors are ineffective in passing a velocity or structural barrier. The design of fishways should present conditions that minimize leaping behaviors (USFWS 2016).

Federal Interagency Passage Design Guidelines

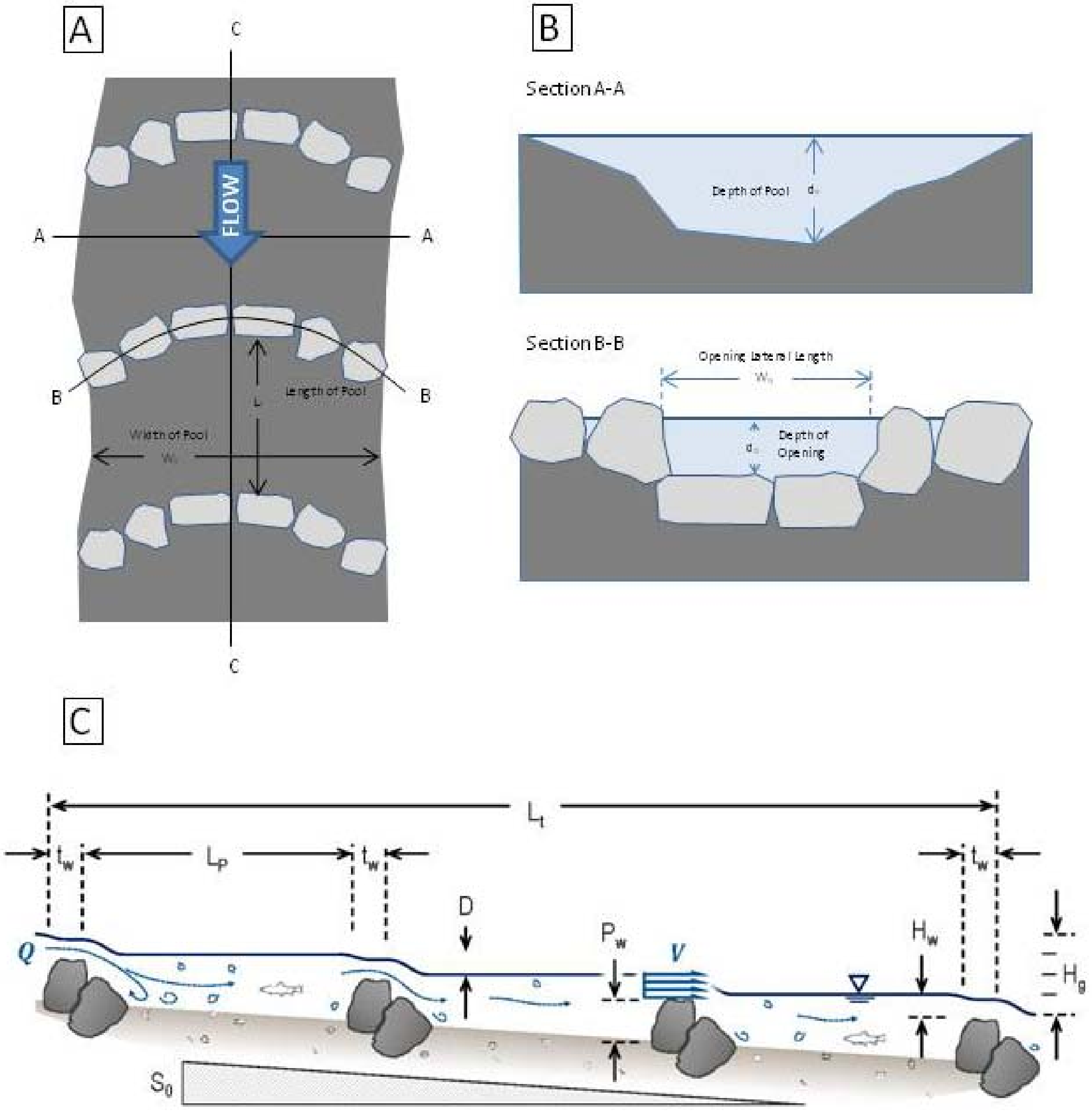
The following are key passage design guidelines that have been identified by the federal interagency team for application to passage of Atlantic Coast diadromous species, and for some species, more discrete guidelines according to life stage/body size categories for the species. These guidelines may be updated by the agencies as additional flume experiments, respirometer and other laboratory studies, and/or field research are completed and results become available that address the physiological and/or behavioral requirements, swimming and leaping capabilities, and passage efficiency of these diadromous fishes and/or other migratory species.

General Design Rationale

This section describes body morphologic dimensions which are determinants of passage, followed by a set of seven design guidelines for each species based on these fish biometrics, plus a maximum velocity criterion based on each species swimming capability. Schematic illustrations are provided in **Figure 1** to accompany and help explain the descriptions of these passage guidelines. Some variables labeled in the graphics are not passage guidelines, but relate to the guidelines. Following the set of passage guidelines descriptions, we present **Table 2** which summarizes the passage guidelines for each of the 14 Atlantic Coast diadromous species, including two length categories for American eel and smaller-sized salmonids; and the basis for, and rationales used in developing this set of guidelines for each of the 14 target fish species.

Figure 1. Plan view (A), cross section (B), and profile (C) illustrations of physical features and nominal measures relating to passage design guidelines for a typical boulder step-pool type fishway.

Note: Schematic profile includes variables that relate to passage guidelines including: Q= flow, t_w= thickness of boulder weir, D= hydraulic drop, P_w= height of rock weir crest, H_w= head over the rock weir, H_g= gross head between headpond and tailwater water surface elevations, and L_t= total length of fishway.



Fish Body Morphology (TL_{min}, TL_{max}, BD/TL Ratio): Maximum and minimum total lengths (TL_{max} and TL_{min}, respectively) and body depth (BD) to total length ratio (BD/TL) for each species were determined to the nearest cm from values published in the literature for diadromous fishes in the Atlantic Coast region. For species with limited or no published data available, unpublished data from recent field investigations were used (Refer to sources cited in species rationales section).

Pool Dimensions

Dimensions of a pool are based on the need to create full- or partial-width channels and pools or bypass channels with pools of sufficient size to serve as resting areas for the target fish species and provide for their protection from predators during passage. Larger fish or species that school in large numbers (hundreds to thousands) require wider, deeper, and longer pools.

The anticipated total run size of the target species and co-occurring species assemblages also need to be thoroughly considered in dimensioning pools.

As a guideline, pool dimensions should also be scaled relative to the size of the stream or river channel and existing pool conditions in nearby unaltered reach or reaches of the study river as a reference, and river flows for the specific design reach. This scaling guideline should be applied regardless of whether the design involves a full or partial width of the stream or river targeted for passage restoration, or is a nature-like bypass channel around a dam or other passage barrier that cannot be removed or modified. Each of the following dimensions should be considered in NLF design:

> ***Minimum Pool Width (W_P):*** For full river-width structures, minimum pool width will vary depending on the size of the river or stream channel. For bypass channels, pool width will depend on maximum design width of the bypass, taking into account the proportion of the river flows used to design safe, timely and effective passage through the bypass during the full range of fish run flows at the subject river reach. To maximize energy dissipation, pool volume, and available resting areas, pool widths should generally be made as wide as practicable.
>
> ***Minimum Pool Depth (d_P):*** In general, pools should be sufficiently deep to serve as resting areas, allow for maneuverability, accommodate deep-bodied and schooling species, and offer protection from terrestrial predators. For small streams (e.g., site with watershed area <5 mi^2), the stream/river channel scaling guideline may be difficult to achieve, and the project design team should assess normal pool depth range in nearby reference reach(es) during the fish passage season. For downstream passage, a minimum depth of pools is needed to provide safe passage of fish and prevent injury or stranding of fish passing over a weir or through a weir opening, especially during low-flow outmigration conditions. Height of the fall as well as body mass of each species needs to be taken into account to minimize the potential for injury to out-migrating fish. For all species, a formula for minimum pool depth was derived which includes a minimum depth of 1 ft, plus 3 body depths, plus one additional body depth as a bottom buffer (to accommodate bottom unconformities and roughness); thus, d_p = 1 ft + 4 BD. Final values of the d_p guideline have been rounded up from the calculated value to the nearest 0.25 ft.
>
> ***Minimum Pool Length (L_P):*** Pool length dimensions follow design guidelines similar to the pool widths, but also depths (i.e., maximize energy dissipation, pool volume and available resting areas; accommodate fish body size(s), run size(s), and resting and schooling behaviors). More importantly, pool length also determines overall slope of the fishway for a given drop per pool, so slope must be taken into account when determining minimum pool length (as well as the number of pools for a given design and overall drop). Refer to the Maximum Fishway Channel Slope (S_0) criterion which takes into account both pool length and drop-per-pool.

Minimum Weir Opening Width (W_N): The weir opening width (i.e., weir notch lateral length) relative to fish passage is based on providing a primary passage opening wide enough to accommodate fish body size and swimming mode and schools of upstream migrating target species adults. For sea lamprey and American eel (anguilliform swimmers), W_N equals 2 times the tailbeat amplitude (values from published literature) for the largest sized individual. For sturgeons, which possess a relatively wide body with broad pectoral fins, W_N equals 2 times the body width of the largest-sized individual, including maximum pectoral fin spread during passage. For all other target species, W_N equaled 2 times the maximum total body length. Final values of W_N were rounded up from the calculated value to the nearest 0.25 ft.

The opening width should also be designed for downstream migrating fish that may be oriented obliquely to the flow in a worst-case condition, to minimize potential body contact with (and subsequent injury) the weir-opening sidewall boulders. Wide weir openings also facilitate location of and attraction to the weir opening by fish in broader river reaches and passage sites by providing a flow jet that spans a larger proportion of the total pool width. Weirs will optimally have multiple passage openings, particularly on larger rivers, with varying invert elevations to function over a range of river flows during the passage season(s) and to benefit multiple species with varying swimming capabilities.

Conversely, the passage opening width needs to take into account the pool depth and hydraulics to accommodate the target species. For small streams with limited flows, the passage opening may need to be limited in width to maintain a minimum depth for passage due to very low flows over weirs, and in particular through a notch especially with lowest flows (e.g., flows <5 cfs) during the fish run period. Weirs should be properly designed such that modeled flows through a passage reach should result in submerged weirs or other grade control structures with passage openings, even during the lowest fish run flows. Such a design will result in streaming flow into a pool with water surface elevation at or above the upstream weir opening invert elevation, and preferably backwatering to the weir crest elevation.

Minimum Weir Opening Depth (d_N): Weir opening depths (i.e., weir notch) need to at least accommodate the full depth (vertical depth of body when swimming horizontally) of the body of the largest-sized target species, including extended dorsal and ventral fins to minimize potential for injury. We conservatively established d_N as 3 times the body depth of the largest-sized individual, rounded up to the nearest 0.25 ft. Minimum depths allow freedom of swimming movements and assurance that propulsion and maneuverability by the tail and fins will allow maximum generation of thrust and the ability of fish to maneuver. If limited river flows during the passage season(s) are not a concern, greater passage opening water depth is preferred at locations where schooling fish, like American shad, are passing simultaneously or passing fish are at high risk to predation. Sufficient water depths are also needed to create a low-velocity bottom zone to facilitate ascent by bottom-dwelling or smaller, weaker-swimming species.

The calculated low stream-flow for the target species run period is most critical to designing the weir opening dimensions and to ensure the minimum water depth guideline is attained. Thus, depths of weirs, openings and other passageway features should be designed to accommodate minimum fish-run period flows and low-flow depths. This passage design need is most critical on small streams and watersheds where normal stream flow is limited (e.g., <20 cfs) and flow through a weir opening would be very limited (e.g., <2 cfs).

Maximum Weir Opening Water Velocity (V_{max}): The ability of fish to traverse zones of higher water velocity, particularly through passage openings, is dependent on motivation, physiological capability (sprint swimming speed), and size range of the target species, and the overall distance that the fish must swim through a high-velocity passage zone. For most weir openings in typical fishway designs, the distances and durations that fish must swim to make upstream progress is relatively short (i.e., tens of feet), so fish may be able to swim over weirs or through these openings at prolonged or brief sprint speeds resulting in minimal fatigue. The probability of fish passing upstream through velocity barriers at prolonged or sprint speeds can be calculated for some species based on known high-speed swimming performance or empirical high-speed swimming model data, particularly the critical swim speed for a species (e.g., Weaver 1965, McAuley 1996, Haro et al. 2004). Sprint swimming data, if available, are usually the best data to use to infer maximum weir opening water velocity. However, sprint swimming research has not been conducted and/or sprint swimming curves have not been developed for most Atlantic Coast diadromous fish species, in which case, alternative methods for determining maximum weir opening velocity were used for developing this guideline.

The following rationale was used to determine V_{max} for each species:

1. When sprint swimming data are available, then U_{max} = the sprint swimming speed sustained for 60 sec, for fish of minimum size (TL_{min}).
2. When no sprint swimming data are available, but critical swimming speed (U_{crit}) values have been determined (i.e., from respirometer studies), then U_{max} = 2 times U_{crit} for fish of minimum size (TL_{min}).
3. When no swimming data are available, U_{max} is calculated for a nominal value of 5 BL/sec for subcarangiform swimmers or 3 BL/sec for anguilliform swimmers, for fish of minimum size (TL_{min}).
4. The initial value of U_{max} was adjusted (if necessary) by assessing calculated U_{max} values within the context of other direct fish swimming observations of each species and known velocity barriers (if available; i.e., observed ability to pass a velocity barrier with known water velocity, or best professional judgment, based on experience).
5. V_{max} = U_{max}, rounded down to the nearest 0.25 ft/sec.

The V_{max} applied in each project should be the value associated with the weakest swimming target species. The V_{max} values presented herein for each species are specifically provided for the targeted species expecting to pass over a weir, through a weir opening or other short-distance high velocity zone and into an effective resting area. A V_{max} value should not be misapplied as the guideline for the overall design or diagnostic evaluation of an entire fishway or fish passage reach, where passage length and time of passage would exceed the capability of the target species in sprint swimming mode to pass the site without available resting pools or sites. Such an example may include a rock ramp nature-like fishway constructed at too steep a slope for the target species, and which lacks resting pools, large boulders, or other features providing adequate resting areas.

Maximum Fishway Channel Slope (S_0): The channel slope, S_0, influences energy loss and water velocity over weirs, through weir notches, in pools, and around other in-stream features. In turn, velocity and energy dissipation influence fish behavior and passage efficiency. The friction slope, S_f, is the rate at which this energy is lost along the channel. In prismatic-shaped channels, uniform flow (i.e., flow that is unchanging in the longitudinal direction) occurs when $S_0 = S_f$. In step-pool fishway structures, the average friction slope is equal to the ratio of hydraulic drop-per-pool, D, to pool length plus weir thickness, $L_p + t_w$ (Figure 1). Thus, quasi-uniform or "uniform-in-the-mean" flow is achieved in step-pool fishways when S_0 and the average S_f are equal over the length of the fishway. In most cases, step-pool fishways are designed for this quasi-uniform condition to limit longitudinal flow development (e.g., accelerating flow) and ensure predictable hydraulic conditions in each pool and over each weir.

Quasi-uniform flow establishes a relationship between S_0 and S_f in step-pool structures; however, an additional constraint on S_0 is necessary to safeguard against unacceptably steep fishway designs. Both the pool length and drop-per-pool criteria are based on a species' need for adequate resting space and swimming capability, respectively. Fishway channel slopes based solely on quasi-uniform flow and a friction slope established by the recommended maximum D and minimum L_p may still result in excessive energy dissipation, propagation of velocity from pool to pool, and/or other undesirable conditions. Therefore, a maximum fishway channel slope, S_0, is also recommended. These channel slopes presented herein (Table 2) are conservative estimates based on natural river gradients and sites known to be passable or populated by the target species.

The reader is cautioned that these slope relationships and associated pool and hydraulic drop criteria create an over-determined system (i.e., more equations than unknowns). To avoid conflicting slope constraints, the following procedure is recommended:

1. Based on a species' V_{max} (Refer to Table 2, below), calculate an appropriate D;
2. Based on D and L_p (Table 2), estimate the friction slope, S_f;
3. If $S_f \leq$ channel slope S_0 (Table 2), then set $S_0 = S_f$ and proceed;
   If $S_f > S_0$, then lengthen L_p or add pools to the design to reduce D (while ensuring minimum depth of flow criterion is also met) until $S_f \leq S_0$, and proceed.

Consider the following example for the passage of alewife over a step-pool structure: For this target species, a V_{max} of 6 ft/sec is recommended (Table 2). To provide structural stability, a 3-ft wide rock weir is selected. Using this V_{max} and t_w, a hydraulic analysis results in a maximum drop-per-pool of D= 1.25 ft. For alewife as the target species, a minimum pool length of L_p = 10 ft is recommended (Table 2). This results in a friction slope, S_f = 0.092 which exceeds the specified maximum pool slope of S_0 = 0.05 or 1:20 (Table 2). Accordingly, the geometry needs to be revised to ensure the maximum channel slope criterion is met. The L_p must be increased, D must be decreased, or both until $S_f \leq S_0$.

In general, consistent pool geometry is preferred, but may not be feasible for some passage sites. When site constraints necessitate pools of varying geometry, the procedure above should be applied, iteratively, to each pool-and-weir combination to ensure S_0, S_f, and the other passage criteria are met.

The above methodology integrates species-specific biological criteria from Table 2 and engineering hydraulics. However, it is important to note that fishway geometry is also influenced by other site conditions and target fish species behavioral factors. Additional considerations include substrate stability, channel morphology, immovable boulders/ledge and other natural features that may further constrain the slope of the fishway. Excessively long pool length, which may otherwise meet slope criteria, may decrease motivation of a target species to pass, thus, compromising passage efficiency. As fish passage planning progresses from conceptual to final design, it is critical to verify these parameters with each design modification to ensure that criteria are still met for the weakest target species and over the greatest possible range of hydrologic conditions at the project site.

Other Design Considerations: For moderate and large-sized rivers, multiple weir openings should be provided for safe passage by multiple target species and schools of a species that behaviorally pass in groups (e.g., American shad). The design should consider the diversity of the fish community present in the stream or river. Large rivers with greater spatial habitat diversity typically support a greater number of both resident and anadromous species, with large numbers of fishes seasonally passing upriver often during coincidental, overlapping spawning run periods. A diverse fish assemblage and large numbers of fish passing necessitate multiple passage openings, and benefitting from varying invert elevations and locations along the weir to account for changes in river flow, especially in larger rivers with a diverse fish assemblage and/or widely varying fish run flow range. Weaker-swimming species will use passage openings closer to the river edge and inside river bends where lower flow velocities occur. Weak-swimming species (e.g., minnows, darters) and some species life-stages (e.g., American eel elvers and yellow-phase juveniles) seek out low-velocity, near-bottom conditions not only for passage sites but often as habitat (Aadland 1993).

Regarding passage at weirs, fish will preferentially pass through weir openings, rather than over weir crests. Fish preferentially use streaming flow through openings, as opposed to plunging flows passing over weirs and into resting pools which are often impassible for species with limited leaping capabilities. Although an in-line configuration of weir openings is preferred, primary openings along multiple weirs can be off-set in alignment to prevent propagation of increasing flow velocities through successive weirs or other grade control structures.

Channel size and flow (e.g., bypass channels) should be referenced to both river size and projected run size of the target fish species or fish community assemblage. For example, nature-like bypass fishways sited on large rivers would need to be appropriately sized for flow and run-size capacity. Fishways which are expected to support large runs of target species should include longer and deeper pools to provide sufficient resting areas to accommodate large numbers of fish during peak passage periods.

Figure 2 presents examples of photographed NLF sites constructed in the Northeast region targeted for passage by Atlantic coast diadromous fish species.

Table 2. Summary of design guidelines for NLFs and related to swimming capabilities and safe, timely and efficient passage for Atlantic Coast diadromous fish species. Note: units are expressed in both metric (cm) and English units (feet or feet/sec). See text for informational sources.

Species	Minimum TL (cm)	Maximum TL (cm)	Body Depth/ TL Ratio	Maximum Body Depth (cm)	Minimum Pool/Channel Width (ft)	Minimum Pool/Channel Depth (ft)	Minimum Pool/Channel Length (ft)	Minimum Weir Opening Width (ft)	Minimum Weir Opening Depth (ft)	Maximum Weir Opening Water Velocity (ft/sec)	Maximum Fishway Channel Slope
	TL_{min}	TL_{max}	BD/TL	BD_{max}	W_p	d_P	L_p	W_N	d_N	V_{max}	S_0
Sea Lamprey	60	86	0.072	6.2	10.0	2.00	20.0	0.75	0.75	6.00	1:30
Shortnose Sturgeon	52	143	0.148	21.2	30.0	4.00	30.0	2.75	2.25	5.00	1:50
Atlantic Sturgeon	88	300	0.150	45.0	50.0	7.00	75.0	5.50	4.50	8.50	1:50
American Eel ≤ 15 cm TL	5	15	0.068	1.0	3.0	1.25	5.0	0.25	0.25	0.75	1:20
American Eel >15 cm TL	15	116	0.068	7.9	6.0	2.00	10.0	0.75	1.00	1.00	1:20
Blueback Herring	20	31	0.252	7.8	5.0	2.00	10.0	2.25	1.00	6.00	1:20
Alewife	22	38	0.233	8.9	5.0	2.25	10.0	2.50	1.00	6.00	1:20
Hickory Shad	28	60	0.221	13.3	20.0	2.75	40.0	4.00	1.50	4.50	1:30
American Shad	36	76	0.292	22.2	20.0	4.00	30.0	5.00	2.25	8.25	1:30
Gizzard Shad	25	50	0.323	16.2	20.0	3.25	40.0	3.50	1.75	4.00	1:30
Rainbow Smelt	12	28	0.129	3.6	5.0	1.50	10.0	1.00	0.50	3.25	1:30
Atlantic Salmon	70	95	0.215	20.4	20.0	3.75	40.0	6.25	2.25	13.75	1:20
Sea Run Brook Trout	10	45	0.255	11.5	5.0	2.50	10.0	1.50	1.25	3.25	1:20
Juvenile Salmonid ≤ 20 cm TL	5	20	0.250	5.0	5.0	1.75	10.0	1.25	0.50	2.25	1:20
Atlantic Tomcod	15	30	0.202	6.1	5.0	2.00	10.0	2.00	0.75	0.75	1:30
Striped Bass	40	140	0.225	31.5	20.0	5.25	30.0	9.25	3.25	5.25	1:30

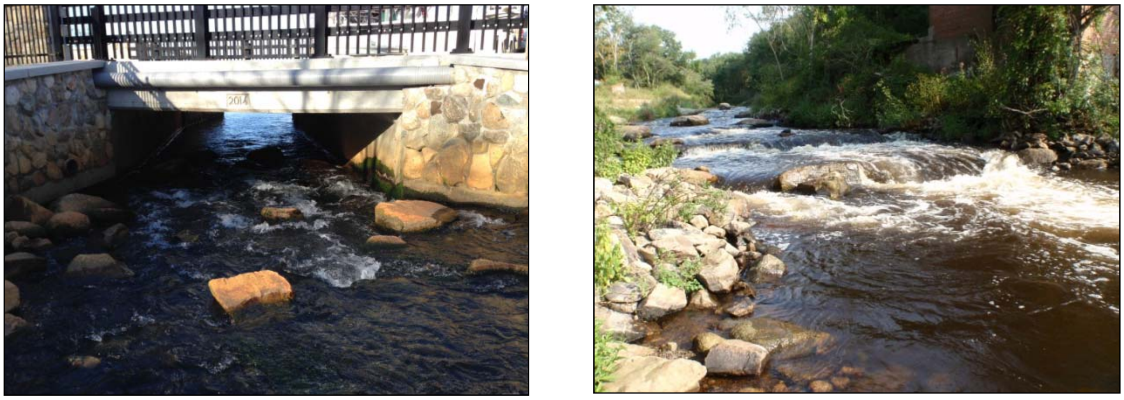
Figure 2. Captioned photographs of nature-like fishways (NLFs) in the Northeast targeting passage of Atlantic coast diadromous fishes (Photo sources: J. Turek, M. Bernier)

Saw Mill Park step-pool fishway,
Acushnet River, Acushnet, MA

Fields Pond step-pool fishway,
Sedgeunkedunk Stream, Orrington, ME

Kenyon Mill step-pool fishway,
Pawcatuck River, Richmond, RI

Homestead dam removal and NLF cross-vanes,
Ashuelot River, West Swanzey, NH



Water Street tidal rock ramp,
Town Brook, Plymouth, MA

Lower Shannock Falls NLF weirs,
Pawcatuck River, Richmond, RI

Species-Specific Rationales

The following passage guidelines rationales for each species are based upon best professional judgment, unless otherwise noted by referenced published literature or other source(s). We applied our experiences with laboratory flume experiments and field observations, and queried other state and federal agency experts in fishery biology and/or fishway engineering design. We note that there is a general paucity of experimental research available, and substantial additional species information is required to verify or refine these guidelines.

Sea Lamprey

TL_{min} = 60 cm (Collette and Klein-MacPhee 2002)
TL_{max} = 86 cm (USFWS Connecticut River Coordinator's Office, unpub. data)
Body Depth/TL Ratio = 0.072 (A. Haro, USGS; unpub. data)

Minimum Pool/Channel Width: **10.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Lamprey tends to rest in pool environments more so than other species, and often aggregate in large numbers while resting. Larger run sizes (hundreds to thousands) will require resting pools wider than this minimum dimension.

Minimum Pool/Channel Depth: **2.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(86 cm * 0.072)* 0.0328) = 1.8 ft. This value was rounded up to d_p = 2.0 ft. Lamprey tends to rest in pool environments more so than other species, and often aggregate in large numbers while resting. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension.

Minimum Pool/Channel Length: **20.0 ft**
The guideline is based on creation of pools large enough to accommodate lamprey body size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. Lampreys tend to rest in pool environments more than other species, and often aggregate in numbers while resting. Larger run sizes (hundreds to thousands) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **0.75 ft**
The minimum opening width guideline is based on a dimension wide enough to accommodate the two times the tailbeat amplitude of the maximum total length (TL) of adult lamprey. Because adult sea lamprey die after spawning, there is no design consideration for downstream passage. Tailbeat amplitude for sea lamprey has been measured as 10% of total length (Bainbridge 1958). Therefore WN = 86 cm * 2 * 0.1 = 17.2 cm = 0.56 ft. This value was rounded up to WN = 0.75 ft.

Minimum Weir Opening Depth: **0.75 ft**

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, lamprey maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} =3 * 6.15 cm = 18.5 cm = 0.61 ft. This value was rounded up to d_N = 0.75 ft.

Maximum Weir Opening Water Velocity: **6.0 ft/sec**

The guideline takes into consideration laboratory sprint swimming studies in an open channel flume (McAuley 1996): approximately 1.0 m/sec swimming speed for a maximum of 60 sec duration for adult lamprey (TL_{min} = 60 cm; U=2 BL/sec). Therefore U_{max} = (2 * 60 cm) = 120 cm/sec = 3.94 ft/sec. However, adult sea lampreys are known to have the capability to free-swim ascend surface weirs in technical fishways at velocities of 8.0 ft/sec (Haro and Kynard 1997). Since laboratory studies and field observations suggest strong but varying swimming capabilities, V_{max} was conservatively established at 6.0 ft/sec.

Maximum Fishway/Channel Slope: **1:30**

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by sea lamprey, or is a conservative estimate of maximum slope based on known sea lamprey swimming behavior and river hydro-geomorphologies in which sea lamprey occurs.

Shortnose Sturgeon

TL_{min} = 52 cm (Collette and Klein-MacPhee 2002)
TL_{max} = 143 cm (Dadswell 1979)
Body Depth/TL Ratio = 0.148 (M. Kieffer, USGS; unpub. data)

Minimum Pool/Channel Width: **30.0 ft**

The guideline is based on pools large enough to serve as sturgeon resting areas and protection from terrestrial predators. Sturgeons typically require larger than average pools, especially if multiple sturgeon are migrating simultaneously through a passageway. While data are lacking for shortnose sturgeon, lake sturgeon are known to use and pass nature-like fishways in groups (L. Aadland, pers. commun.).

Minimum Pool/Channel Depth: **4.0 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(143 cm * 0.148)* 0.0328) = 3.8 ft. This value was rounded up to d_p = 4.0 ft. Sturgeons typically require larger than average-sized pools, especially if multiple sturgeon are migrating simultaneously through a passageway.

Minimum Pool/Channel Length: **30.0 ft**

The guideline is based on pools large enough to accommodate sturgeon body size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. Shortnose sturgeon may aggregate in large numbers while resting in pools. Larger run sizes (hundreds or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **2.75 ft**
The minimum opening width guideline is based on a dimension wide enough to accommodate two times the total body width (including pectoral fin spread) of the maximum total length (TL) of adult shortnose sturgeon. Data are lacking for total body span (including pectoral fins) for shortnose sturgeon, but have been estimated as 27% of TL in lake sturgeon (L. Aadland, Minnesota Department of Natural Resources, pers. comm.). Therefore, W_N = 143 cm * 2 * 0.27 = 77.2 cm = 2.53 ft. This value was rounded up to W_N = 2.75 ft.

Minimum Weir Opening Depth: **2.25 ft**
The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, sturgeon maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} =3 *21.19 cm = 63.6 cm = 2.09 ft. This value was rounded up to d_N = 2.25 ft.

Maximum Weir Opening Water Velocity: **5.0 ft/sec**
No sprint swimming data are available for adult shortnose sturgeon; U_{crit} for adult shortnose sturgeon is unknown. Based on maximum U=3 BL/sec for anguilliform swimmers and affording passage of smallest sized adults, U_{max} = 3 * 52 cm = 156 cm/sec = 5.12 ft/sec. This value was rounded down to V_{max} = 5.0 ft/sec.

Maximum Fishway/Channel Slope: **1:50**
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by shortnose sturgeon, or is a conservative estimate of maximum slope based on known shortnose sturgeon swimming behavior and river hydro-geomorphologies in which this sturgeon species occurs.

Atlantic Sturgeon

TL_{min} = 88 cm (M. Kieffer, USGS, unpub.data)
TL_{max} = 300 cm (M. Kieffer, USGS, unpub.data)
Body Depth/TL Ratio = 0.150 (M. Kieffer, USGS, unpub.data)

Minimum Pool/Channel Width: **50.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Sturgeons typically require larger than average pools, especially if multiple sturgeon are migrating simultaneously through a passageway.

Minimum Pool/Channel Depth: **7.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1

ft + 4BD_{max}: d_p = 1 ft + (4*(300 cm * 0.150)* 0.0328) = 6.9 ft. This value was rounded up to d_p = 7.0 ft. Sturgeons typically require larger than average-sized pools, especially if multiple sturgeon are migrating simultaneously through a passageway.

Minimum Pool/Channel Length: **75.0 ft**
The guideline is based on creation of pools large enough to accommodate sturgeon body size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. Atlantic sturgeon may aggregate in large numbers while resting in pools. Larger run sizes (hundreds or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **5.50 ft**
The minimum opening width guideline is based on a dimension wide enough to accommodate two times the total body width (including pectoral fin spread) of the maximum total length (TL) of adult Atlantic sturgeon. Data are lacking for total body span (including pectoral fins) for Atlantic sturgeon, but have been estimated as 27% of TL in lake sturgeon (L. Aadland, Minnesota Department of Natural Resources, pers. comm.). Therefore, W_N = 300 cm * 2 * 0.27 = 162 cm = 5.31 ft. This value was rounded up to W_N = 5.50 ft.

Minimum Weir Opening Depth: **4.5 ft**
The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, sturgeon maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} = 3 * 45.00 cm = 135.0 cm = 4.43 ft. This value was rounded up to d_N = 4.5 ft.

Maximum Weir Opening Water Velocity: **8.5 ft/sec**
No sprint swimming data are available for adult Atlantic sturgeon; U_{crit} for adult Atlantic sturgeon is unknown. Based on U=3 BL/sec for anguilliform swimmers; U_{max} = (3 * 88 cm) = 264 cm/sec = 8.66 ft/sec. This value was rounded down to V_{max} = 8.5 ft/sec.

Maximum Fishway/Channel Slope: **1:50**
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by Atlantic sturgeon, or is a conservative estimate of maximum slope based on known Atlantic sturgeon swimming behavior and river hydro-geomorphologies in which sturgeon occur.

American Eel $\leq$ 15 cm ($\leq$6 inch) TL

TL_{min} = 5 cm (Haro and Krueger 1991)
TL_{max} = 15 cm (upper limit of specified range)
Body Depth/TL Ratio = 0.068 (A. Haro, USGS, unpub.data)

Small ($\leq$15 cm TL) American eels (elvers and small juveniles) are usually upstream migrants, passing through low-velocity flows along river edges and through openings, voids, and crevices in natural and man-made barriers and other riverside structures. Small eels can also climb wetted surfaces for significant distances, aided by water-surface tension. Small eels therefore may only require small openings or passageways, preferably along low-velocity river edges, where they commonly congregate. Design guidelines were developed for two eel size classes since eels continue upstream migration for multiple years and eels may not ascend to distant upstream sites during elver/small juvenile eel stage. These upstream sites are more likely to only pass larger, older, yellow eels; guidelines for elvers and small eels would therefore not apply. Size distribution of eels should be assessed at sites considered for nature-like fishway planning before guidelines for upstream eel passage are applied in design. Guidelines for this size range do not take into account downstream passage; see next Section (American Eel > 15 cm TL) for downstream passage guidelines relevant to adult ("silver" phase) or larger, downstream-moving juvenile ("yellow phase") American eel.

Minimum Pool/Channel Width: **3.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. American eels tend to rest in pool environments more so than other species, and young eels often aggregate in large numbers while resting, particularly within the substrate. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: **1.25 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(15 cm * 0.068)* 0.0328) = 1.1 ft. This value was rounded up to d_p = 1.25 ft. American eel tend to rest in pool environments more so than other species, and young eels often aggregate in large numbers while resting, particularly within the substrate. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension.

Minimum Pool/Channel Length: **5.0 ft**
The guideline is based on creation of pools large enough to accommodate eel body size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. American eel tend to rest in pool environments more so than other species, and young eels often aggregate in large numbers while resting in pools. Larger run sizes (thousands or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **0.25 ft**
The minimum opening width guideline is based on a dimension wide enough to accommodate the two times the tailbeat amplitude of the maximum total length (TL) of small American eels. Tailbeat amplitude for American eels has been measured as 8% of total length (Gillis 1998). Therefore W_N = 15 cm * 2 * 0.08 = 2.4 cm = 0.08 ft. This value was rounded up to W_N = 0.25 ft. However, as adults, eels may migrate downstream through weir openings, so a larger weir opening width may be required.

Minimum Weir Opening Depth: **0.25 ft**

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} =3 *1.02 cm = 3.1 cm = 0.10 ft). This value was rounded up to d_N = 0.25 ft. However, as adults, eels may migrate downstream through weir openings, so a larger opening may be required (See *American Eel > 15 cm TL; Minimum Weir Opening Depth*).

Maximum Weir Opening Water Velocity: **0.75 ft/sec**

The guideline is based on laboratory sprint swimming studies (McCleave 1980): U=4.6 BL/sec swimming speed for maximum 60 sec duration for 5 cm TL elvers in an open channel test flume. Therefore, U_{max} = 4.6 * 5 cm = 23 cm/sec = 0.75 ft/sec. V_{max} was established at 0.75 ft/sec.

Maximum Fishway/Channel Slope: **1:20**

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by juvenile American eel, or is a conservative estimate of maximum slope based on known eel swimming behavior and river hydro-geomorphologies in which eel occur.

American Eel > 15 cm (>6 inch) TL

TL_{min} = 15 cm (lower limit of specified range)
TL_{max} = 116 cm (Tremblay 2009)
Body Depth/TL Ratio = 0.068 (A. Haro, USGS, unpub.data)

Minimum Pool/Channel Width: **6.0 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. American eels tend to rest in pool environments more so than other species, and often aggregate in large numbers while resting, particularly within the substrate. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: **2.0 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(116 cm * 0.068)* 0.0328) = 2.0 ft. American eels tend to rest in pool environments more so than other species, and often aggregate in large numbers while resting, particularly within the substrate. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension.

Minimum Pool/Channel Length: **10.0 ft**

The guideline is based on creation of pools large enough to accommodate fish size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. American eel tend to rest in pool environments more so than other species, and often aggregate in large numbers while resting in pools. Larger run sizes (thousands or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: 0.75 ft

The minimum opening width guideline is based on a dimension wide enough to accommodate the two times the tailbeat amplitude of the maximum total length (TL) of larger American eels. Tailbeat amplitude for American eels has been measured as 8% of total length (Gillis 1998). Therefore, W_N = 116 cm * 2 * 0.08 = 18.6 cm = 0.61 ft. This value was rounded up to W_N = 0.75 ft. However, as adults, eels may migrate downstream through weir openings, so a larger weir opening width may be required.

Minimum Weir Opening Depth: 1.0 ft

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} =3 * 7.9 cm = 23.4 cm = 0.76 ft. This value was rounded up to d_N = 1.0ft.

Maximum Weir Opening Water Velocity: 1.0 ft/sec

The guideline is based on mean U_{crit} = 0.43 m/s for eels of mean length 44 cm eel; U= 0.97 BL/sec in respirometer experiments (Quintella et al. 2010). Therefore, U_{max} = 2 * 0.97 * 15 cm = 29.1 cm/sec = 0.95 ft/sec. This value was rounded up to V_{max} = 1.0 ft/sec.

Maximum Fishway/Channel Slope: 1:20

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by American eel, although juvenile eels are capable of ascending substrates with steeper slopes having roughened surfaces and/or interstitial spaces within boulders, cobbles or other structures.

Blueback Herring

TL_{min} = 20 cm (Collette and Klein-MacPhee 2002)
TL_{max} = 31 cm (S. Turner, NMFS, unpub. data)
Body Depth/TL Ratio = 0.252 (A. Haro, USGS, unpub. data)

Minimum Pool/Channel Width: 5.0 ft

The guideline is based on pools large enough to serve as resting areas and protection of adults from terrestrial predators. Blueback herring is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands or more) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: 2.0 ft

The guideline is based on pools large enough to serve as resting areas and protection of adults from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(31 cm * 0.252)* 0.0328) = 2.0 ft. Blueback herring is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (thousands or more) will require pools deeper than this minimum dimension. This depth guideline may not be feasible on very small-sized, first- and second-order streams with small watersheds (e.g., <5 mi^2), limited stream flows, and smaller run sizes (hundreds of fish or less).

Minimum Pool/Channel Length: 10.0 ft
The guideline is based on pools large enough to accommodate herring body size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. Blueback herring is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (thousands or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: 2.25 ft
The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult blueback herring oriented in "worst case" perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2 * 31 cm = 62 cm = 2.03 ft. This value was rounded up to W_N = 2.25 ft. In the case of larger populations (thousands or greater), entrance dimensions should be greater than 2.25 ft, or multiple openings of this minimal dimension should be constructed in weirs to accommodate multiple groups of fish simultaneously passing through the weir opening(s).

Minimum Weir Opening Depth: 1.0 ft
The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, herring maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} =3 * 7.81 cm = 23.4 cm = 0.77 ft. This value was rounded up to d_N = 1.0 ft.

Maximum Weir Opening Water Velocity: 6.0 ft/sec
The guideline is based on laboratory sprint swimming studies in an open channel flume (Haro et al. 2004, Castro-Santos 2005): U=6 BL/sec swimming speed for a maximum 60 sec. Therefore U_{max} = (6 * 20 cm) = 120 cm/sec = 3.94 ft/sec. However, adult blueback herring are known to ascend surface weirs, natural ledge drops, and technical fishways at velocities of 8.0 ft/sec or higher (Reback et al. 2004). To address the varying data currently available, V_{max} was established at 6.0 ft/sec.

Maximum Fishway/Channel Slope: 1:20
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by blueback herring (Franklin et al. 2012), or is a conservative estimate of maximum slope based on known blueback herring swimming behavior and river hydro-geomorphologies in which blueback herring occur.

Alewife

TL_{min} = 22 cm (Collette and Klein-MacPhee 2002)
TL_{max} = 38 cm (Collette and Klein-MacPhee 2002)
Body Depth/TL Ratio = 0.233 (G. Wippelhauser, Maine Div. Marine Fisheries, unpub. data)

Minimum Pool/Channel Width: 5.0 ft
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Alewife is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: 2.25 ft
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(38 cm * 0.233)* 0.0328) = 2.2 ft. This value was rounded up to d_p = 2.25 ft. Alewife is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension. This depth guideline may not be feasible on very small-sized, first- and second-order streams with small watersheds (e.g., <5 mi^2), limited stream flows, and smaller run sizes (hundreds of fish or less).

Minimum Pool/Channel Length: 10.0 ft
The guideline is based on creation of pools large enough to accommodate alewife body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines. Alewife is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (thousands or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: 2.50 ft
The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult alewife oriented in a “worst case” perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2* 38 cm: = 76 cm = 2.49 ft. This value was rounded up to W_N = 2.50 ft. In the case of larger stream populations (thousands or greater), entrance dimensions should be increased above 2.5 ft or multiple openings should be constructed in weirs to accommodate large numbers of fish simultaneously passing through the weir opening(s).

Minimum Weir Opening Depth: 1.0 ft
The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 8.86 cm = 26.6 cm = 0.87 ft. This value was rounded up to d_N = 1.0 ft.

Maximum Weir Opening Water Velocity: 6.0 ft/sec
The guideline is based on laboratory sprint swimming studies in an open channel test flume (Haro et al. 2004, Castro-Santos 2005): U=5.5 BL/sec swimming speed for a maximum 60 sec. Therefore U_{max} = 5.5 * 22 cm = 121 cm/sec = 3.97 ft/sec. In contrast, field observations have revealed adult alewives may ascend surface weirs in technical fishways at velocities of 8.0 ft/sec or higher (Reback et al. 2004) . To address the varying test data available, V_{max} was established at 6.0 ft/sec.

Maximum Fishway/Channel Slope: **1:20**

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by alewife (Franklin et al. 2012), or is a conservative estimate of maximum slope based on known alewife swimming behavior and river hydro-geomorphologies in which alewives occur.

Hickory Shad

TL_{min} = 28 cm (Collette and Klein-MacPhee 2002)
TL_{max} = 60 cm (Klauda et al. 1991)
Body Depth/TL Ratio = 0.221 (FishBase; www.fishbase.org; BD = 22.1% of TL)

Minimum Pool/Channel Width: **20.0 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Hickory shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: **2.75 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(60 cm * 0.221)* 0.0328) = 2.7 ft. This value was rounded up to d_p = 2.75 ft. Hickory shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension.

Minimum Pool/Channel Length: **40.0 ft**

The guideline is based on creation of pools large enough to accommodate shad body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines. Hickory shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **4.0 ft**

The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult hickory shad oriented in a “worst case” perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2*60 cm = 120 cm = 3.94 ft. This value was rounded up to W_N = 4.00 ft. In the case of larger populations (thousands or greater), entrance dimensions should be greater than 4.00 ft, or multiple openings should be constructed in weirs to accommodate multiple shad simultaneously passing through weir opening(s).

Minimum Weir Opening Depth: **1.5 ft**

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max} =3 * 13.3 cm = 39.8 cm = 1.31 ft. This value was rounded up to d_N = 1.50 ft.

Maximum Weir Opening Water Velocity: **4.5 ft/sec**
No sprint swimming data are available for hickory shad. U_{crit} for hickory shad is unknown. Based on U=5 BL/sec for subcarangiform swimmers, U_{max} = 5 * 28 cm = 140 cm/sec = 4.59 ft/sec. This value was rounded down to V_{max} = 4.50 ft/sec.

Maximum Fishway/Channel Slope: **1:30**
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by hickory shad, or is a conservative estimate of maximum slope based on known hickory shad swimming behavior and river hydro-geomorphologies in which hickory shad occur.

American Shad

TL_{min} = 36 cm (MacKenzie 1985)
TL_{max} = 76 cm (Klauda et al. 1991)
Body Depth/TL Ratio = 0.292 (A. Haro, USGS, unpub. data (Connecticut River fish))

Minimum Pool/Channel Width: **20.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. American shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension, typically on moderate to large-sized Atlantic Coast rivers (i.e., >200-1,000+ mi^2 watersheds).

Minimum Pool/Channel Depth: **4.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(76 cm * 0.292)* 0.0328) = 3.9 ft. This value was rounded up to d_p = 4.0 ft. American shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension, typically on moderate to larger-sized rivers (i.e., >200-1,000+ mi^2 watersheds).

Minimum Pool/Channel Length: **30.0 ft**
The guideline is based on creation of pools large enough to accommodate shad body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines. American shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (thousands or greater) will require pools longer than this minimum dimension, typically on moderate to large-sized rivers (i.e., >200-1,000+ mi^2 watersheds).

Minimum Weir Opening Width: **5.0 ft**

The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult American shad oriented in a "worst case" perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2*76 cm: = 152 cm = 4.99 ft. This value was rounded up to W_N = 5.00 ft. In the case of larger populations (thousands or greater), entrance dimensions should be greater than 5.00 ft or multiple openings should be constructed. Multiple fish simultaneously passing through weir openings are frequently observed in passage structures designed for large runs of America shad (Haro and Kynard 1997).

Note, in the southern portion of its range, particularly from Florida north to North Carolina, mature American shad are somewhat smaller (lengths: 35-47 cm; 1.2-1.6 ft) and have a higher percentage of single-time spawners than adult shad comprising more northerly populations (Facey and Van Den Avyle 1986). South of Cape Hatteras, North Carolina, American shad die after spawning (termed, semelparous), with increasing repeat spawning (iteroparous) with increasing latitude north of Cape Hatteras (Leggett and Carscadden 1978).

Minimum Weir Opening Depth: **2.25 ft**

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 22.2 cm= 66.6 cm = 2.18 ft. This value was rounded up to d_N = 2.25 ft. As noted above, smaller-sized adults in the southern Atlantic Coast populations may support a lesser passage opening depth based on the body depth of adults in these populations.

Maximum Weir Opening Water Velocity: **8.25 ft/sec**

The guideline is based on laboratory sprint swimming studies in an open channel test flume (Haro et al. 2004; Castro-Santos 2005): U=7.0 BL/sec swimming speed for a maximum 60 sec. Therefore U_{max} = 7.0 * 36 cm = 252 cm/sec = 8.27 ft/sec. This value was rounded down to V_{max} = 8.25 ft/sec.

Maximum Fishway/Channel Slope: **1:30**

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by American shad, or is a conservative estimate of maximum slope based on known American shad swimming behavior and river hydro-geomorphologies in which shad occur.

Gizzard Shad

TL_{min} = 25 cm (Miller 1960)
TL_{max} = 50 cm (Able and Fahay 2010)
Body Depth/TL Ratio = 0.323 (FishBase; www.fishbase.org; BD = 32.3% of TL)

Minimum Pool/Channel Width: **20.0 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Gizzard shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: **3.25 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(50 cm * 0.323)* 0.0328) = 3.1 ft. This value was rounded up to d_p = 3.25 ft. Gizzard shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension.

Minimum Pool/Channel Length: **40.0 ft**

The guideline is based on creation of pools large enough to accommodate shad body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines. Gizzard shad is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (thousands or greater) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **3.5 ft**

The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult gizzard shad in a "worst case" perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2*50 cm: = 100 cm = 3.28 ft. This value was rounded up to W_N = 3.5 ft. In the case of larger populations (thousands or greater), entrance dimensions should be greater than 3.5 ft or multiple openings provided to accommodate multiple fish simultaneously passing through the weir opening(s).

Minimum Weir Opening Depth: **1.75 ft**

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 16.2 = 48.5 cm = 1.59 ft, to provide additional depth for maneuvering, passage by shad schools, and use of lower velocity zone. This value was rounded up to d_N = 1.75 ft.

Maximum Weir Opening Water Velocity: **4.0 ft/sec**

No known sprint swimming data are available for gizzard shad; U_{crit} for gizzard shad is unknown. The guideline is therefore based on U= 5 BL/sec for subcarangiform swimmers; U_{max} = 5 * 25 cm = 125 cm/sec = 4.10 ft/sec. This value was rounded down to V_{max} = 4.0 ft/sec.

Maximum Fishway/Channel Slope: **1:30**

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by gizzard shad, or is a conservative estimate of maximum slope based on known gizzard shad swimming behavior and river hydro-geomorphologies in which gizzard shad occur.

Rainbow Smelt

TL_{min} = 12 cm (C. Enterline, Maine Department of Marine Resources, unpub. data)
TL_{max} = 28 cm (C. Enterline, Maine Department of Marine Resources, unpub. data; Data from O'Malley (2016) for anadromous smelt from four Maine rivers (2010-2014) indicate maximum length of 24 cm, perhaps suggesting a temporal trend in decreasing mean length in Northeast smelt populations)
Body Depth/TL Ratio = 0.129 (FishBase; www.fishbase.org; BD = 12.9% of TL)

Minimum Pool/Channel Width: **5.0 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Rainbow smelt is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools wider than this minimum dimension.

Minimum Pool/Channel Depth: **1.5 ft**
The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(28 cm * 0.129)* 0.0328) = 1.5 ft. Rainbow smelt is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools deeper than this minimum dimension.

Minimum Pool/Channel Length: **10.0 ft**
The guideline is based on creation of pools large enough to accommodate fish size, run size, and resting and schooling behavior, as well as meeting minimum weir velocity and maximum energy dissipation and slope guidelines. Rainbow smelt is a schooling species and often aggregates in large numbers while resting in pools. Larger run sizes (hundreds to thousands) will require pools longer than this minimum dimension.

Minimum Weir Opening Width: **1.0 ft**
The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult rainbow smelt in a "worst case" perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2*28 cm = 56 cm = 1.84 ft . This value was reduced to W_N = 1.0 ft to offset potential flow limitations during low fish-run flow periods for passageways on small to very small (first or second-order) coastal streams where wider openings may result in shallow water depths not meeting the passage opening depth guideline (See minimum weir opening depth guideline, below) . In the case of larger populations (thousands or greater), entrance dimensions should be greater than1.0 ft to accommodate multiple fish simultaneously passing through the weir opening.

Minimum Weir Opening Depth: **0.50 ft**
The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 3.6 cm = 10.8 cm = 0.35 ft. This value was rounded up to d_N = 0.50 ft.

Maximum Weir Opening Water Velocity: **3.25 ft/sec**

The guideline is based on mean U_{crit} = 0.30 m/s for 7 cm, smaller-sized adult rainbow smelt in respirometer experiments (Griffiths 1979); U_{crit} = 4.29 BL/sec. Therefore U_{max} = 2 * 4.29 * 12 cm = 103.0 cm/sec = 3.38 ft/sec. Velocity barriers have been observed for rainbow smelt at water velocities greater than 3.9 ft/sec (B. Chase, MADMF, pers. comm., 8/30/2011). V_{max} was rounded down to 3.25 ft/sec.

Maximum Fishway/Channel Slope: **1:30**

Rainbow smelt spawning runs are typically associated with low-gradient streams and rivers near the head-of-tide. Slope guidelines have not been previously established for rainbow smelt, so a conservative slope was selected. This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by rainbow smelt, or is a conservative estimate of maximum slope based on known rainbow smelt swimming behavior and river hydro-geomorphologies in which smelt occur.

Atlantic Salmon

TL_{min} = 70 cm (T. Sheehan, NMFS, unpub. data)
TL_{max} = 95 cm (T. Sheehan, NMFS, unpub. data)
Body Depth/TL Ratio = 0.215 (T. Sheehan, NMFS, unpub. data; these data were applied to best represent current Northeastern U.S. populations)

Minimum Pool/Channel Width: **20.0 ft**

The guideline is based on creation of pools large enough to serve as resting areas and protection from terrestrial predators.

Minimum Pool/Channel Depth: **3.75 ft**

The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(95 cm * 0.215)* 0.0328) = 3.7 ft. This value was rounded up to d_p = 3.75 ft.

Minimum Pool/Channel Length: **40.0 ft**

The guideline is based on creation of pools large enough to accommodate salmon body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines.

Minimum Weir Opening Width: **6.25 ft**

The guideline is based on a weir opening dimension wide enough to accommodate downstream movement of adult Atlantic salmon in a “worst case” perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2*95 cm = 190 cm = 6.23 ft. This value was rounded up to W_N = 6.25 ft. This width dimension may be reduced to offset potential flow limitations not meeting the minimum weir opening water depth guideline (See water depth guideline, below) associated with low-flow (e.g., autumn post-spawn downstream passage) conditions during the passage season.

Minimum Weir Opening Depth: **2.25 ft**

The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 20.41 cm = 61.2 cm = 2.01 ft. This value was rounded up to d_N = 2.25 ft.

Maximum Weir Opening Water Velocity: **13.75 ft/sec**

The guideline is based initially on mean U_{crit} = 1.70 m/s for 57 cm adult Atlantic salmon in respirometer experiments (Booth et al. 1997). The 57 cm body length approximates the smallest-sized, sea-run adult salmon (grilse) and is not based on smaller-sized spawning adult landlocked salmon; U_{crit}= 3.0 BL/sec. Therefore, U_{max} = 2 * 3.0 * 70 cm = 420 cm/sec = 13.78 ft/sec. This value was rounded down to V_{max} = 13.75 ft/sec.

Maximum Fishway/Channel Slope: **1:20**

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by Atlantic salmon, or is a conservative estimate of maximum slope based on known Atlantic salmon swimming and leaping behavior and river hydro-geomorphologies in which Atlantic salmon occur.

Sea-Run Brook Trout

TL_{min} = 10 cm (M. Gallagher, Maine Department of Inland Fisheries, unpub. data)
TL_{max} = 45 cm (M. Gallagher, Maine Department of Inland Fisheries, unpub. data)
Body Depth/TL Ratio = 0.255 (M. Gallagher, Maine Dept. Inland Fisheries, unpub. data)

Minimum Pool/Channel Width: **5.0 ft**

The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators. Streams and rivers with larger runs (hundreds or more) will require greater passage widths.

Minimum Pool/Channel Depth: **2.5 ft**

The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators, as well as accommodating trout leaping capabilities and needs for passing over weirs or through openings. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(45 cm * 0.255)* 0.0328) = 2.5 ft.

Minimum Pool/Channel Length: **10.0 ft**

The guideline is based on creation of pools large enough to accommodate trout body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines.

Minimum Weir Opening Width: **1.5 ft**

The guideline is based on a weir dimension wide enough to accommodate downstream movement of adult sea-run brook trout in a “worst case” perpendicular orientation to the flow, equivalent to 2 times TL_{max} or 2*45 cm: = 90 cm = 2.95 ft. However, this dimension was reduced to W_N = 1.5 ft. to offset potential flow limitations not meeting the minimum weir opening water depth guideline (See minimum weir opening water depth guideline, below) associated with low-flow (e.g., autumn post-spawn downstream passage) conditions during the passage season for passages on small or very small (first or second-order) coastal streams.

Minimum Weir Opening Depth: **1.25 ft**
The guideline is based on provision of sufficient water depth through the weir opening to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 11.5 cm = 34.4 cm = 1.12 ft. This value was rounded up to d_N = 1.25 ft.

Maximum Weir Opening Water Velocity: **3.25 ft/sec**
The guideline is based initially on laboratory sprint swimming studies in an open channel flume (Castro-Santos et al. 2013): U=10.0 BL/sec swimming speed for a maximum 60 sec. Therefore, U_{max} = 10.0 * 10 cm = 100 cm/sec = 3.28 ft/sec. This value was rounded down to V_{max} = 3.25 ft/sec.

Maximum Fishway/Channel Slope: **1:20**
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by sea-run brook trout, or is a conservative estimate of maximum slope based on known brook trout swimming behavior and river hydro-geomorphologies in which brook trout occur.

Smaller-sized Salmonids $\leq$20 cm ($\leq$8 inch) TL

TL_{min} = 5 cm (lower limit of specified range)
TL_{max} = 20 cm (upper limit of specified range)
Body Depth/TL Ratio = 0.250 (generalized BD/TL ratio)

We present guidelines for smaller-sized salmonids which may include both non-migratory phase Atlantic salmon parr (juveniles) using low-order, high-gradient streams with limited seasonal flows; and native sea-run brook trout which may mature as adults as small as 8.5-cm length, and are typically found in Northeast streams and rivers at smaller-size lengths.

Minimum Pool/Channel Width: **5.0 ft**
The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators.

Minimum Pool/Channel Depth: **1.75 ft**
The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators, as well as accommodating leaping capabilities and needs of juvenile salmonids. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(20 cm * 0.250)* 0.0328) = 1.7 ft. This value was rounded up to d_p = 1.75 ft.

Minimum Pool/Channel Length: **10.0 ft**
The guideline is based on creation of pools large enough to accommodate fish size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines.

Minimum Weir Opening Width: **1.25 ft**
The guideline is based on a weir dimension wide enough to accommodate downstream movement of upstream passage by a larger juvenile or young adult, and the downstream movement of juvenile salmonids and smolts in a "worst case" perpendicular orientation to the flow, equivalent to 2 times TL_{max} of 20 cm: = 40 cm = 1.31 ft. However this value was rounded down to W_N = 1.25 ft to offset potential flow limitations not meeting the minimum weir opening water depth guideline (See minimum weir opening water depth guideline, below) associated with low fish-run flow conditions for passageways on small or very small (first or second-order) coastal streams and streams with substantially varying ("flashy") seasonal flow conditions.

Minimum Weir Opening Depth: **0.50 ft**
The guideline is based on provision of sufficient water depth through the weir opening to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 5.0 cm = 15.0 cm = 0.49 ft. This value was rounded up to d_N = 0.50 ft.

Maximum Weir Opening Water Velocity: **2.25 ft/sec**
The guideline is based on mean U_{crit} = 0.62 m/s for 8.5 cm brook trout in respirometer experiments (McDonald et al. 1998); U= 7.3 BL/sec. This guideline is based on the approximate smallest body length for adult brook trout. Therefore, U_{max} = 2 * 7.3 * 5.0 cm = 73.0 cm/sec = 2.40 ft/sec. This value was rounded down to V_{max} = 2.25 ft/sec.

Maximum Fishway/Channel Slope: **1:20**
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by juvenile salmonids, or is a conservative estimate of maximum slope based on known salmonid swimming and leaping behavior and river hydro-geomorphologies in which salmonids occur.

Atlantic Tomcod

TL_{min} = 15 cm (Collette and Klein-MacPhee 2002)
TL_{max} = 30 cm (Collette and Klein-MacPhee 2002, Stevens et al., 2016)
Body Depth/TL Ratio = 0.202 (FishBase; www.fishbase.org; BD = 20.2% of TL)

Minimum Pool/Channel Width: **5.0 ft**
The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators.

Minimum Pool/Channel Depth: 2.0 ft

The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(30 cm * 0.202)* 0.0328) = 1.8 ft. This value was rounded up to d_p = 2.0 ft.

Minimum Pool/Channel Length: 10.0 ft

The guideline is based on creation of pools large enough to accommodate tomcod body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines.

Minimum Weir Opening Width: 2.0 ft

The guideline is based on a weir dimension wide enough to accommodate upstream passage by multiple adult Atlantic tomcod migrating upstream in small tidal, coastal streams, including during ebbing-tide periods in tidal streams; as well as downstream movement of adult Atlantic tomcod in a "worst case" perpendicular orientation to the flow; equivalent to 2 times TL_{max} or 2*30 cm: = 60 cm = 1.97 ft. This value was rounded up to W_N = 2.0 ft.

Minimum Weir Opening Depth: 0.75 ft

The guideline is based on provision of sufficient water depth through the weir opening to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 6.06 cm = 18.2 cm = 0.60 ft. This value was rounded up to d_N = 0.75 ft.

Maximum Weir Opening Water Velocity: 0.75 ft/sec

No sprint swimming data are available for Atlantic tomcod. U_{crit} for Atlantic tomcod is unknown. Water velocities in excess of 30 cm/sec are known to be barriers for Atlantic tomcod (Bergeron et al. 1998); therefore, U_{max} = 30 cm/sec = 0.98 ft/sec. This value was rounded down to V_{max} = 0.75 ft/sec. If a passage site is affected by tidal flooding, tom cod may alternatively passively move over project site weirs or through weir openings or other hydraulic features during diurnal flood tide events.

Maximum Fishway/Channel Slope: 1:30

This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by tom cod, or is a conservative estimate of maximum slope based on known tom cod swimming behavior and river hydro-geomorphologies in which tom cod occur.

Striped Bass

TL_{min} = 15 cm (Fay et al. 1983)
TL_{max} = 30 cm (Collette and Klein-MacPhee 2002)
Body Depth/TL Ratio = 0.225 (FishBase; www.fishbase.org; BD = 22.5% of TL)

Minimum Pool/Channel Width: **20.0 ft**
The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators.

Minimum Pool/Channel Depth: **5.25 ft**
The guideline is based on creating pools large enough to serve as resting areas and protection from terrestrial predators. Minimum pool depth was calculated using the formula 1 ft + $4BD_{max}$: d_p = 1 ft + (4*(140 cm * 0.225)* 0.0328) = 5.1 ft. This value was rounded up to d_p = 5.25 ft.

Minimum Pool/Channel Length: **30.0 ft**
The guideline is based on creation of pools large enough to accommodate bass body size, run size, and resting and schooling behavior, as well as meeting maximum weir opening velocity and maximum energy dissipation and slope guidelines.

Minimum Weir Opening Width: **9.25 ft**
The guideline is based on a weir dimension wide enough to accommodate upstream migration by adult striped bass on migratory spawning runs (principally tidal rivers with varying tidal prism, or larger (fourth+-order) non-tidal rivers); and downstream movement of adult striped bass in a "worst case" perpendicular orientation to the flow; equivalent to at least 2 times TL_{max} or 2*140 cm: = 280 cm = 9.19 ft. This value was rounded up to W_N = 9.25 ft.

Minimum Weir Opening Depth: **3.25 ft**
The guideline is based on provision of sufficient water depth over the weir to enable protection from terrestrial predators, maneuvering in low flows, and use of lower velocity zone in high flows; equivalent to 3 times BD_{max}: 3 * 31.5 cm= 94.5 cm = 3.10 ft. This value was rounded up to d_N = 3.25 ft.

Maximum Weir Opening Water Velocity: **5.25 ft/sec**
The guideline is based on laboratory sprint swimming studies in an open channel test flume (Haro et al. 2004; Castro-Santos 2005): U=4.0 BL/sec swimming speed for a maximum 60 sec. Therefore U_{max} = 4.0 * 40 cm = 160 cm/sec = 5.25 ft/sec. V_{max} was therefore established as 5.25 ft/sec for smaller-sized striped bass.

Maximum Fishway/Channel Slope: **1:30**
This nominal slope guideline approximates the maximum slope at natural river sites known to be passable by striped bass, or is a conservative estimate of maximum slope based on known striped bass swimming behavior and river hydro-geomorphologies in which striped bass occur.

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