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Passage of American Shad: Paradigms and Realities

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Abstract
Despite more than 250 years of development, the passage of American shad *Alosa sapidissima* at dams and other barriers frequently remains problematic. Few improvements in design based on knowledge of the swimming, schooling, and migratory behaviors of American shad have been incorporated into passage structures. Large-scale technical fishways designed for the passage of adult salmonids on the Columbia River have been presumed to have good performance for American shad but have never been rigorously evaluated for this species. Similar but smaller fishway designs on the East Coast frequently have poor performance. Provision of effective downstream passage for both juvenile and postspawning adult American shad has been given little consideration in most passage projects. Ways to attract and guide American shad to both fishway entrances and downstream bypasses remain marginally understood. The historical development of passage structures for American shad has resulted in assumptions and paradigms about American shad behavior and passage that are frequently unsubstantiated by supporting data or appropriate experimentation. We propose that many of these assumptions and paradigms are either unfounded or invalid and that significant improvements to American shad upstream and downstream passage can be made via a sequential program of behavioral experimentation, application of experimental results to the physical and hydraulic design of new structures, and controlled tests of large-scale prototype structures in the laboratory and field.

> There is a field for some inventive mind, because no one has as yet invented a means whereby the shad will go up. [Statement by a Mr. Graham in Dyche (1912)]

The American shad *Alosa sapidissima* was historically an abundant anadromous fish that ascended major North American river systems from Florida to southeastern Newfoundland (Bigelow and Schroeder 1953). Hundreds of thousands or even millions of fish ascended larger rivers during the spring upstream migration. Prior to 1900, landings in Canada and the northeastern United States exceeded several million pounds (Scott and Crossman 1973). Declines in populations have been attributed to dams, pollution, and overfishing (Stevenson 1897; MacKenzie et al. 1985), but the proportional contribution of each of these factors to the decline is unknown. Given that American shad regularly migrated hundreds of kilometers upstream in large rivers, the effect of constructing dams that completely excluded them from upstream spawning habitat was probably significant. However, dam construction did not completely extirpate populations in rivers in which there was spawning habitat downstream of the first impassable dam, and remnant spawning populations persisted in the lower reaches of most major rivers. Because American shad home to natal rivers (Melvin et al. 1986) and even tributaries (Carscadden and Leggett 1975), dams probably affected the demographics of the original populations (e.g., age structure, sex ratio, extent of repeat spawning, etc.) to some degree. Where dams completely blocked all access to spawning habitat, populations were either reduced to reproductively unsustainable levels (typically in smaller rivers or tributaries) or extirpated.

EARLY PASSAGE EFFORTS

In North America, initial attempts to mitigate barriers to fish passage caused by dams focused almost exclusively on

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Atlantic salmon *Salmo salar*, American shad, and alewives *A. pseudoharengus* (Atkins 1873). Attempts to provide passage for American shad occurred as early as 1739 on tributaries of the Connecticut River (Hallock 1875). These efforts initially involved the creation of passage channels by forming step pools in the natural bedrock at the base of a dam or piling rocks to create weirs or backwaters, so that American shad would at least be able to ascend to the dam crest. In the late 1800s, fishway designs were employed that were thought to pass adult salmonids and trout in Canada and Europe. These fishways were usually of higher slope (greater than 10%), with turbulent hydraulics, and usually passed fewer American shad than expected. However, the term "success" with respect to early assessments of passage performance has to be applied with caution, as evaluations of fishway performance from the late 1800s to the mid-1900s were largely qualitative in nature, relying heavily on simple observations of fish traversing a structure or accumulating in large numbers below a dam and not on rigorous quantitative evaluation techniques. There are few or no quantitative data on the numbers passed or fishway passage efficiency from 19th-century fishways.

Other problems with proper fishway siting and the creation of appropriate entrance flows and hydraulics also appeared to limit the performance of these structures. Early fishways were often constructed of wood, stone, cribwork, or other materials that were easily destroyed by high flow conditions, and as a result they were frequently modified and rebuilt. Nonetheless, early North American fishways were of varied and imaginative design and included modified dam notches, step pools, and often-complex pool-and-weir and reverse-flow designs (Atkins 1873; McDonald 1883; Figure 1). A few fishways constructed in mid-Atlantic rivers appear to have been specifically designed for American shad, given that salmon did not occur in this region and American shad were the dominant anadromous species.

After 1900, fishways became larger and were more commonly constructed from concrete and steel yet often still had a high slope or extensive length. Typical designs were of the pool-and-weir type, often with many similarly sized pools, which were assumed to be successful in larger rivers with adult salmonids (Orsborn 1987). At low-head dams, simple notches or ramps were constructed (Moffitt et al. 1982); these passed large volumes of water that appeared to attract American shad to enter the structure. However, they also forced fish to swim against high water velocities in order to ascend. Although modest numbers of American shad were noted to pass some fishway designs (Rogers 1892; Collins 1951), large numbers of American shad continued to accumulate below dams despite the presence of a fishway. It should be noted that little or no accumulation of fish below a barrier does not necessarily equate to "good" passage performance, but it may be an indicator of such. However, the trend of poor passage of American shad in traditional fishway designs continued throughout the early 20th century; so little progress was made that in 1923 the U.S. Bureau of Fisheries was prompted to conclude that "[i]t is very doubtful if shad would ascend a fishway of any description or any height" (Whitney et al. 1961). Considerable effort was also made in the late 1800s and early 1900s to propagate American shad for both restoration programs and as a way to ameliorate migratory barriers (dams) by stocking cultured American shad larvae above dams, often in lieu of any provision for the upstream passage for adults. Concerns were also raised as early as the late 1800s about the safe and effective downstream passage of both postspawning adult and juvenile American shad (Rogers 1892), yet it appears that no steps were taken at that time to provide downstream protection or passageways for either life stage.

LOCKS AND LIFTS

Few accounts of the effectiveness of navigational locks for passing American shad are available before the mid-1900s, although more recent assessments have indicated problems. American shad frequently either fail to enter navigational locks, are not retained in the lock during the locking cycle, or fail to exit the lock after the locking cycle (Moser et al. 2000; Bailey et al. 2004). The effectiveness of fish locks (e.g., pressure or Borland-type fish locks designed and constructed expressly for passing fish) for American shad has been variable; an early prototype operated in the 1950s at Holyoke Dam on the Connecticut River performed poorly for American shad and other species (Dalley 1980; Moffitt et al. 1982). Conversely, the fish locks at Bonneville Dam on the Columbia River passed hundreds of thousands of American shad annually (Talbot 1953) and purportedly were equally as effective in passing American shad as the large Bonneville Dam fishways in the early 1940s; however, their use was discontinued after only several years of operation due to mechanical and maintenance problems.

The first fish lift in the United States was built at Holyoke Dam on the Connecticut River in 1955 and passed American shad, although it initially suffered from operational problems and the fish had to be removed from the lift bucket by hand (Walburg and Nichols 1967), with some mortality (Dalley 1980). Later refinements to the Holyoke lift design led to improvements in efficiency and capacity, although problems with attraction into the lift remained (Barry and Kynard 1986). The relative success of the Holyoke lift in passing American shad led to the development of similar designs at higher dams on the St. Johns, Merrimack, and Susquehanna rivers, although there was still the problem of attracting fish into the lift entrances rather than the competing flows from tailraces (Jessop 1975; Sprankle 2005). Overcrowding of American shad in lift buckets during peak run periods and injuries from contact with the crowder and lift machinery were also noted (Jessop 1975; Larinier and Travade 2002).

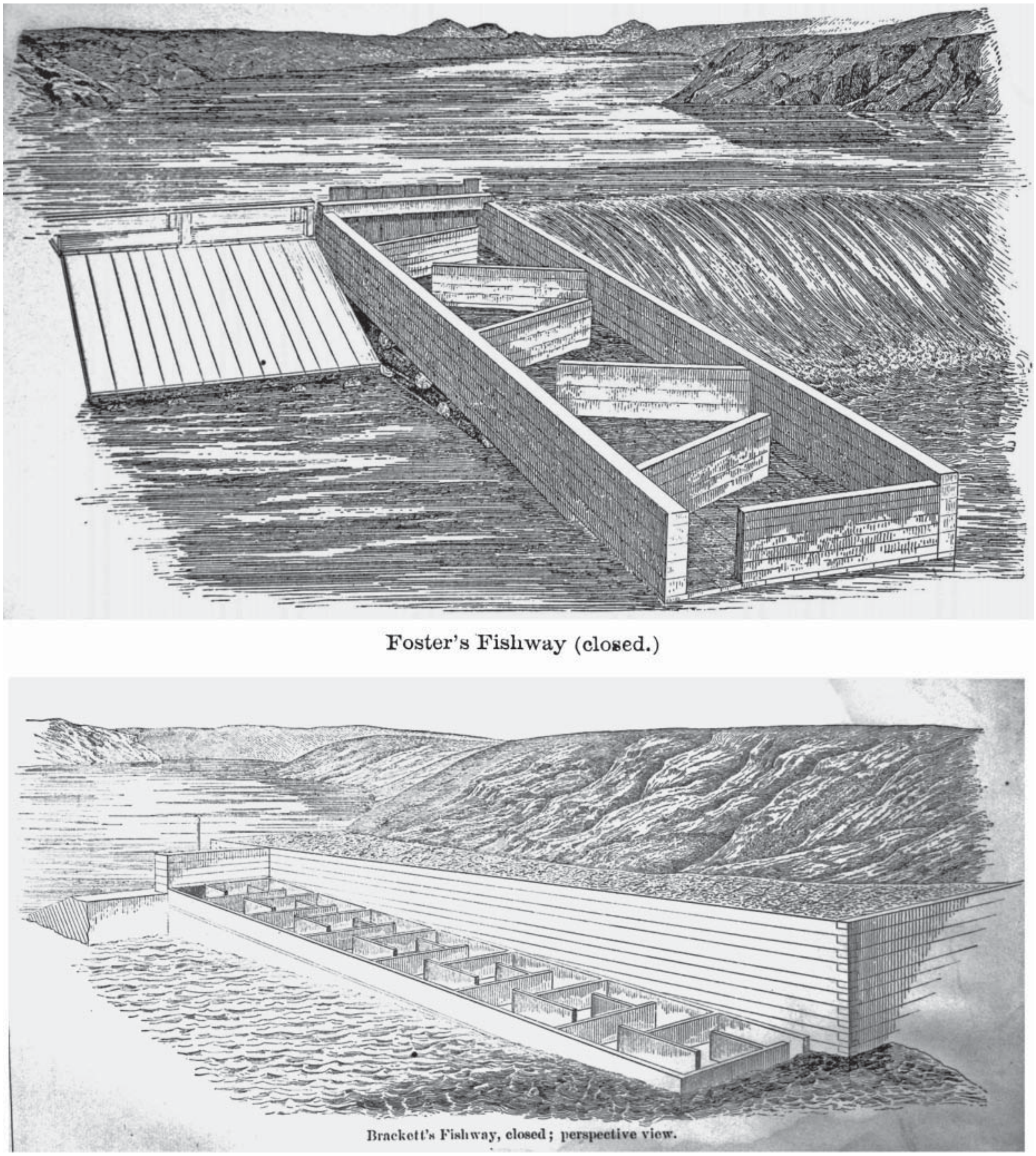

FIGURE 1. Examples of late-19th-century fishway designs. These and other designs were commonly constructed on the main stems and tributaries of North American rivers and intended to pass American shad as well as other species. The performance of these designs in passing American shad is largely undocumented, but failures were common (from Atkins 1873).

MODERN TECHNICAL FISHWAYS

American shad in the Columbia River (Washington and Oregon) were observed to pass the large, technical pool-and-weir fishways constructed in 1937 for adult salmonids at Bonneville Dam (Talbot 1953; Walburg and Nichols 1967; Figure 2), and presently several million American shad pass annually after extensive modifications in the 1960s and 1970s (Petersen et al. 2003). Additional refinements to the full-width overflow weir design of the Bonneville fishways resulted in the partial-width overflow Ice Harbor fishway design and several other large-scale fishway designs that also passed large numbers of American shad on the upper Columbia River. However, American shad were reluctant to enter submerged orifices in an upper regulating section of the fishway at John Day Dam, resulting in

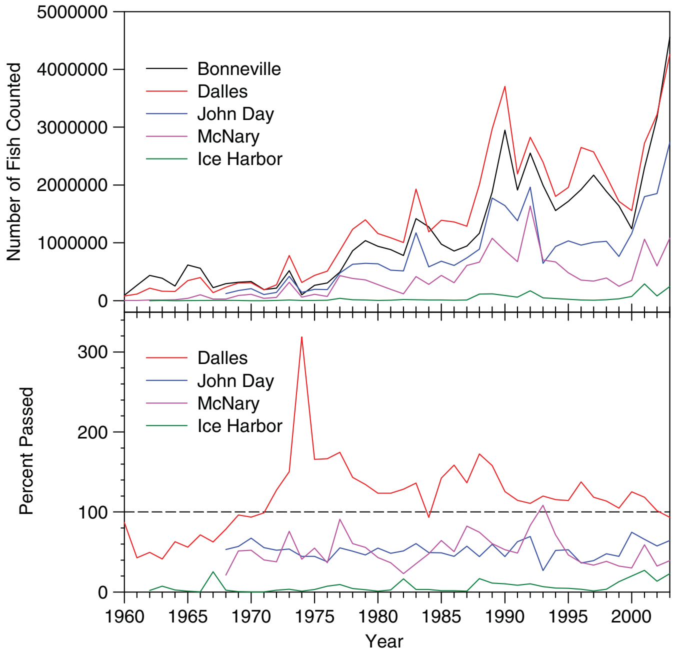

FIGURE 2. Absolute and relative passage of American shad at lower Columbia River main-stem dams, 1960–2003, as quantified by counts of fish at fishway counting windows. The upper panel shows the annual counts from all of the fishways at each dam; the lower panel shows the passage at each dam as a percentage of the fish passed from the next dam downstream. Although the percent passage sometimes exceeds 100%, indicating counting error, there is also a relative consistency in the percent passage for each dam over the long term. These data should not be interpreted as an absolute measure of the passage performance of fishways, given that they combine data from different fishways, include window count error, and do not exclude the effects of the failure of fish to ascend a between-dam reach or those of fishway attraction. Nonetheless, managers in the 1960s and 1970s interpreted the sheer numbers of American shad passed as evidence of the favorable performance of these large fishways for American shad. Data are from the Northwest Power Planning Council's Fish Passage Center (http://www.fpc.org/).

overcrowding and high mortality in the upper fishway; modification of these weirs with partial-depth side slots improved passage for both American shad and salmon (Monk et al. 1989). Additional experimentation at the Fisheries-Engineering Research Laboratory at Bonneville Dam (Collins and Elling 1961; Weaver 1965) added significant knowledge about American shad passage, swimming performance, and behavior. New fishway modifications were developed and constructed to specifically accommodate both American shad and salmon (Weaver et al. 1972), yet no specific quantitative evaluation of the performance of any of the existing Columbia River fishways in passing American shad was performed, despite extensive telemetry studies of adult salmonids in the late 1900s. As an extension of these designs, a low-slope (1:15) vertical slot upper regulating section at the John Day fishway passed 73.1% of American shad in experimental tests (Weaver et al. 1972); this technical fishway design is unique in that it typically has overall slopes of 6.7% or less (Johnson and Perkins 1968), but the effective slope (linear path of flow from slot to slot) may be much lower. Hydraulic drops though slots in this design may also be 0.25 m or less with little air entrainment, and flows through the fishway are more linear, with fewer eddies. This design has been cited as more favorable for American shad passage (Larinier and Travade 2002), but no quantitative field evaluation of this design has been performed for American shad.

Passage of the Anadromous Fish Conservation Act in 1965 renewed interest in fish passage efforts and prompted states to seek federal aid in promoting the restoration of American shad on many major river systems (Moffitt et al. 1982). The presumed favorable performance of the Columbia River fishway designs in passing large numbers of American shad (still without any supporting quantitative performance evaluation data) encouraged engineers to design and construct similar, yet smaller-scale fishways (e.g., Ice Harbor, vertical slot) for American shad, salmon, and other anadromous species on East Coast rivers in the 1970s. However, the initial numbers of American shad passed by many of these scaled-down fishways were disappointingly low (Rideout et al. 1985; Quinn 1994), with fish apparently being reluctant to enter the fishways, ascending only a limited distance, or milling and overcrowding in the turnpools.

Modifications to the weir structures of Cabot Fishway (Connecticut River, Massachusetts) to enhance the streaming flow within pools raised the annual numbers of American shad passed from hundreds to tens of thousands (Rideout et al. 1985), though this was still only about 5% of the total number of shad lifted at the next dam downstream, Holyoke Dam. Further investigations indicated that there were significant upstream and downstream movements within the fishway, milling behaviors in fishway pools, and fallback of fish out of the fishway at night (Haro and Kynard 1997), suggesting continued poor passage efficiency. Passage at Cabot Fishway has been more recently quantified using passive integrated transponder telemetry and found to be only 2–25% of the number of fish that enter the fishway (Sullivan 2004; A. Haro, unpublished data; Figure 3), with some variability in overall passage between years. Fishway hydraulics unfavorable to American shad passage (i.e., turbulence, air entrainment, and plunging flows) were suspected as the cause of the poor passage of Cabot Fishway, yet never specifically identified as causative agents. The great vertical height (22 m) and corresponding length (220 m) of the fishway probably resulted in relatively long transit times for American shad (median, 10.2 h; Sullivan 2004). Similar poor passage has been noted in other scaled-down vertical-slot fishways having relatively high overall slopes of 10% and vertical drop per pool of greater than 0.3 m (Arnold 2000; Weaver et al. 2003; Perillo and Butler 2009). Slots narrower than 0.3 m also were thought to increase the risk of body contact with slot walls, causing descaling and other potentially injurious effects (Quinn 1994). Based on these observations, conventional high-slope (≥10%) pool-and-weir fishway designs have been considered inappropriate for the passage of American shad and given way to full-depth vertical-slot designs with a maximum drop of 0.25 m per pool (Quinn 1994);

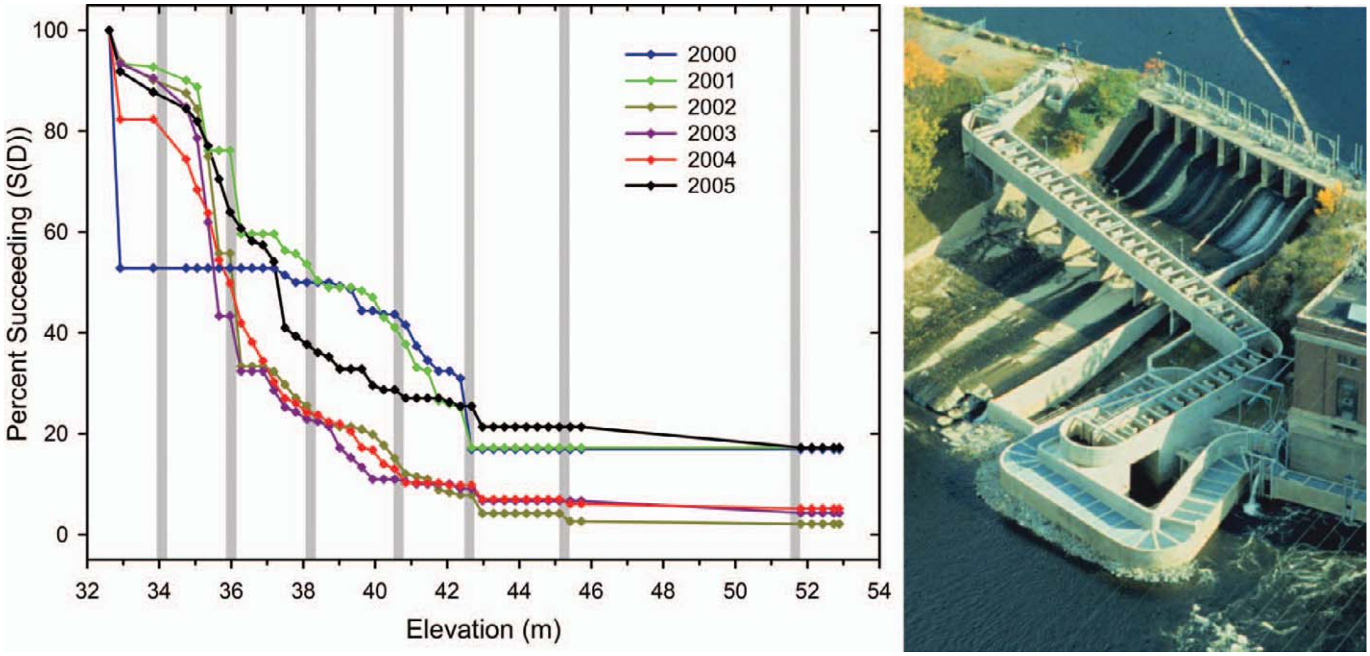

FIGURE 3. Passage of American shad via the 22-m-high Cabot Fishway (Ice Harbor pool-and-weir design; Turners Falls, Connecticut River) expressed as a percentage of the fish entering the fishway as determined by passive integrated transponder (PIT) telemetry from 2000 to 2005. Forty-five PIT antennas (points) were located throughout the fishway (elevation at entrance, 32.5 m; elevation at exit, 53 m); the gray bars indicate the locations of turnpools. Note the low overall percent passage with some variability between years and the consistent pattern of failure within specific regions of the fishway. (From Sullivan 2004 and Haro and Castro-Santos, unpublished data.)

even so, there have been few quantitative evaluation studies of vertical-slot designs for this species.

BAFFLE FISHWAYS

American shad are known to pass baffle-type fishways, including traditional Denil (Haro et al. 1999) and Alaska steeppass (Slatick and Basham 1985; Haro et al. 1999) fishways at slopes up to 28%; however, American shad were unable to completely ascend an experimental steeppass fishway greater than 20 m in length with a 27.3% slope (Slatick and Basham 1985). Entrance and exit conditions (water depths and velocities) influenced the entry and passage of American shad in an experimental steeppass fishway, with fish preferring steeppass fishway entrances with greater depth (Slatick 1975); American shad were much more reluctant than adult Pacific salmonids to enter steeppass fishways. American shad also tended to be initially reluctant to continue upstream from turning or resting pools in baffle fishways, resulting in passage delays and failures (A. Haro and T. Castro-Santos, unpublished data). Larger (1.2-m-wide) traditional Denil (plane baffle) fishways have been constructed for American shad, which may pass them in moderate numbers when slopes are low and fishway lengths are short (Dalley 1980; Haro et al. 1999). Shad are suspected to have more difficulty than salmonids in negotiating the helical current patterns inside baffle fishways (Larinier and Travade 2002). Given their unreliable performance for the passage of allis shad (also known as allice shad) *A. alosa*, baffle fishways are typically not constructed for the passage of this species in Europe (M. Larinier, Institut de Mécanique des Fluides, personal communication).

BEHAVIOR AND SWIMMING PERFORMANCE

Observations and experiences with fish passage structures for American shad throughout the past century have led to some generalized paradigms of American shad behavior that are thought to be important for passage design. American shad tend to be diurnal in their migratory habits and to enter and pass upstream passage structures primarily during the day (Fisher 1997; Haro and Kynard 1997; Sullivan 2004), while falling back to lower-velocity zones at night (Theiss 1997). They are also somewhat reluctant to immediately pass under darkened areas of open channels (e.g., under low bridges or strong shadows, or where there is a strong light transition). American shad school as both juveniles and adults and are less inclined to separate from a school in order to pass a structure or zone of high water velocity (Larinier and Travade 2002). Pool-and-weir or other fishways with numerous resting pools may disrupt school integrity by separating individual fish from schools within pool segments. Similarly, channel constrictions or other physical transitions may create barriers for single fish or entire schools. Submerged orifices are typically not used when ascending fishways (Monk et al. 1989), with American shad preferring surface weirs or slots with free surface flow. Laminar or streaming flows are considered to be a preferred hydraulic condition within a fishway, and flows with significant turbulence, air entrainment, hydraulic jumps, and upwelling are thought to be generally avoided (Larinier and Travade 2002). However, there are no controlled experiments or data that specifically address the behavioral preference of American shad for these flow conditions, and this species will volitionally enter highly turbulent and air-entrained flows of baffle fishways. American shad may also mill or otherwise become "trapped" in large recirculating eddies of fishway resting and turnpools, resulting in large numbers of fish accumulating in these structures.

Unlike salmon, American shad do not generally leap to ascend waterfalls or high-velocity zones (Larinier and Travade 2002), but they can swim at sprint speeds for short distances to ascend zones of high water velocities, occasionally at water depths less than their body depth (Haro et al. 2004). American shad in an experimental, open-channel flume were observed to progress upstream up to 6.1 m against water velocities as high as 4.15 m/s (Weaver 1965) and an average of 5 m against a water velocity of 4.5 m/s (Haro et al. 2004). American shad can swim in sprint mode at through-water swimming speeds of up to 20 body lengths/s (Castro-Santos 2005), exceeding the sprint swimming performance of some adult salmonids. American shad may make repeated attempts to transit a velocity barrier or passage structure via sprint swimming but tend to discontinue attempting to pass a structure after a relatively short time period (Castro-Santos 2002). American shad have a high metabolic rate in comparison with other teleost fishes, and upstream migration is more energetically costly for this species than for other anadromous fishes (e.g., salmon; Leonard et al. 1999). However, American shad show few signs of physiological exhaustion as a result of ascending long pool-and-weir fishways (Leonard and McCormick 1999).

DOWNSTREAM PASSAGE

The mortality of adult American shad passing through turbines is not well studied but largely depends on turbine design, rotation speed, blade spacing, and other factors. Immediate postpassage mortality has been measured as 10–12% in Kaplan and mixed flow turbines (Heisey et al. 2008), 24.2% for larger Kaplan turbine runners (Bell and Kynard 1985), and 21.5–46.3% in a large Straflo low-head tidal turbine (Hogans and Melvin 1985). Higher mortality rates are to be expected in smaller or faster-rotating turbines (Montén 1985). Being smaller than adults, juvenile American shad have comparatively low turbine mortality rates in conventional hydroelectric turbines, usually less than 5% in large Kaplan turbines (Heisey et al. 1992; Mathur et al. 1994) but up to 46.3% in a large Straflo low-head tidal turbine (Stokesbury and Dadswell 1991). Direct estimation of the turbine mortality of small, fragile juvenile American shad is technically difficult and the methods for quantification of mortality in small fish vary widely (e.g., penstock or tailrace netting versus mark–recapture methods). The mortality of American shad adults and juveniles caused by passage via spill has not been extensively evaluated, although that of juveniles passing an open-channel, downstream bypass chute can be less than 2% (RMC Environmental Services 1995).

Various methods have been evaluated to behaviorally exclude juvenile and adult American shad from entrainment in intake structures. Adult American shad were repelled by high frequency (161.9-kHz) acoustic fields in both the laboratory and a canal, but sound was less effective in guiding or excluding American shad moving rapidly downstream with the flow (Kynard and O'Leary 1990). Juvenile American shad can be likewise repelled from intakes by high frequency sound (Mann et al. 2001) and strobe lights (Martin and Sullivan 1992; EPRI 1992). Adult American shad have also been shown to be sensitive to an AC electrical field of 0.25 V/cm, but this field did not present a complete barrier to movement. Higher-voltage electric fields were used to immobilize adult American shad in order to "force" them to enter a downstream bypass exit, but this technique was not efficient (Kynard and O'Leary 1993). It has been generally concluded that it is difficult to guide downstream migrant adult American shad with any behavioral barrier (Kynard and O'Leary 1990). Repulsion of juveniles and adults from intakes does not automatically imply safe and effective protection, as fish must still find a bypass entrance or other safe route downstream past the barrier. Fish excluded from an intake may thus be significantly delayed in their downstream migration, which can result in deleterious energy expenditures and potential migration failure.

Adult American shad were effectively guided by experimental louvers (Kynard and Buerkett 1997) set at an angle of 20 degrees to the flow but avoided entering louver bypass exits with rates of water velocity increase of $0.44\ \mathrm{m \cdot s^{-1} \cdot m^{-1}}$. Similar guidance and avoidance behaviors were noted in the field at the Holyoke Dam Canal (Connecticut River) louver system (NUSCo and Harza Engineering Co. 1992). Juvenile American shad were reluctant to pass accelerating flows of $2\ \mathrm{m \cdot s^{-1} \cdot m^{-1}}$ at surface bypass entrances; this avoidance behavior was reduced at acceleration rates of $1\ \mathrm{m \cdot s^{-1} \cdot m^{-1}}$ (Haro et al. 1998).

DESIGN GUIDELINES FOR PASSAGE STRUCTURES FOR AMERICAN SHAD

Development of specific design criteria for the upstream passage of American shad has been ongoing, but many of the generic design considerations now in place (Table 1) still hark back to the presumed favorable fishway design characteristics that were noted in the late 1800s (schooling behaviors, the reluctance of American shad to enter dark areas, the negative effects of turbulence or poor fishway hydraulics, the need for large attraction flows, etc.; Atkins 1873). Much of the current understanding of American shad passage requirements still relies on qualitative observation or general experience and is only minimally based on hypothesis-based experimentation and

TABLE 1. Common design recommendations for fish passage structures. Comparison of differences in application and design recommendations for various upstream fish passage structures for American shad from three primary sources. Recommendations from Larinier and Travade (2002) apply generically to both American shad and allis shad.

Structure type	Walburg and Nichols (1967)	Quinn (1994)	Larinier and Travade (2002)
Pool-and-weir fishways	Minimum pool size, 2.4 m wide × 2.4 m long × 1.2 m deep; maximum drop per pool, 0.25 m; maximum velocity in resting pools, <0.3 m/s	Minimum pool size, 3 m long × 1.3 m deep; maximum drop per pool, 0.25 m; minimum depth over surface weirs, streaming flow, 0.35 m; minimum vertical slot width, 0.4 m	"Large" pools; minimum total volume, 12 m^3; minimum depth, 1.2 m; weirs or slots oriented along walls, 0.45-m minimum width; maximum prop per pool, 0.3 m (0.2–0.25 m preferred); no deep submerged orifices, minimum recirculation, aeration and turbulence; maximum energy dissipation factor, 150 W/m^3
Baffle fishways	No recommendation	Minimum width, 1.2 m; maximum slope, 1:8 (12.5%); baffles at 45° with 0.71 m clear spacing; minimum water depth, 0.76 m; maximum vertical rise without resting pool, 2–3 m; maximum flow, 4.5–10.5 m^3 /s	Not recommended
Fish lift	Appropriate, but no specifications given	Recommended for low- or high-head dams; no specifications given	Crowding pool minimum 5 m long × 2.5 m wide × 1.5 m deep, 30 L of water per fish; lift bucket sized based on numbers of shad expected at peak of run, 10 L of water per fish; exit channel minimum, 1.5 m wide; minimum water velocity, 0.3 m/s
Fish lock	Minimum lock size 2.4 m wide × 2.4 m long × 1.2 m deep; dependent on number of fish to be passed	Recommended for low- or high-head dams; no specifications given	Not recommended; low-head dams only; not enclosed
Navigation lock	Similar to fish locks	Appropriate, but no specifications given	Required minimum attraction flows for fish to enter and exit lock; maximize number of lockages per day
Notches/ breaches	No recommendation	Maximum 1 m total head differential; maximum 4.3 m/s water velocity; minimum 1-m depth pool beneath notch	No recommendation
Entrances	Minimum 1.8 m wide × 0.3–1 m deep; velocities <1 m/s; transport channels minimum 2.4 m wide × 1.2 m deep	Up to 3% of total turbine capacity for attraction flow	Higher entrance flows, minimum water velocity of 2 m/s; entrance located along bank; collection gallery recommended when tailrace exceeds 20 m in width

design grounded in fish behavior. At present, most conventional fishway designs largely retain the characteristics of traditional salmonid fishways or structures meant to pass a wide variety of species (e.g., fish lifts). Newer designs of passage structures such as nature-like fishways presently lack specific design criteria for the passage of American shad; problems with the passage of other species suggest that these designs still remain questionable and that design criteria require additional development. Although dam removals may seem intuitively favorable for American shad passage (Beasley and Hightower 2000), aspects of postremoval hydraulics and operation that do not impede passage of this species still need to be defined and taken into account in the removal design process. Similarly, design criteria for the downstream passage of juvenile and adult American shad (e.g., intake screen size, approach velocities, and acceptable levels of entrainment or turbine mortality) are not fully developed or at least defined.

SUMMARY: PARADIGMS AND REALITIES

Over the last 250 years, some progress has been made in improving upstream passage for American shad in fishways and other structures, yet the performance of even the most advanced structures is still not as high as it is for adult salmonids. This has led to a generalized paradigm that high performance cannot be achieved for American shad in any conventional fishway design, with 50% efficiency being viewed as "excellent" and 75% efficiency as "exceptional" (Larinier and Travade 2002). The root causes of poor fishway performance for American shad are for the most part unknown and may lie as much in the lack of attraction to a fishway entrance as to passage efficiency within a fishway. Attraction becomes especially important with modern or rehabilitated dams, where available river flow is at a premium and attraction flow is commonly limited to less than 3% of total project generation flow. Conversely, spill conditions at a dam and the resulting competing flows may make it difficult for fish to locate fishway entrances that have proportionately low attraction flow. However, future experimentation to more specifically determine the conditions that American shad find attractive (e.g., entrance configuration and siting and entrance water velocities) may enhance attraction and passage performance when an increase in attraction flow is not a viable option. Any measure to decrease delays in the passage of American shad, whether at the attraction or in-fishway passage phase, can also be beneficial, as the loss of energy reserves from delays at barriers can have significant consequences in terms of energetics and reproductive success (Glebe and Leggett 1981; Castro-Santos and Letcher 2010). Future assessments of the performance of upstream and downstream passage structures will need to take passage performance over time (e.g., delays) into account in addition to absolute passage efficiency, especially for this species.

The design of passage structures for American shad can certainly be improved, and steps toward this end may lead to structures that enhance passage efficiency and reduce transit time. The development of upstream passage structures to accommodate a wider range of species usually requires lower water velocities and less turbulent flows to pass smaller species. Although this may be beneficial for American shad, they may also find entrances with reduced velocities less attractive than entrances with higher velocities. The advent of fish lifts created the potential for the rapid, high-volume passage of American shad at high-head dams where long fishways were impractical or inappropriate, yet the problems of attraction to fish lifts (e.g., entrance siting and competing high-volume flow from tailraces) and capacity at peak run periods still need to be resolved.

Solutions to the problem of effective downstream passage of American shad also remain undeveloped. The paradigm that the provision of effective downstream passage for both juveniles and adults is unnecessary frequently prevails, and the assumption that downstream passage structures that have been shown to be effective for juvenile Atlantic salmon *Salmo salar* are equally effective for American shad is rarely validated. The downstream passage mortality of adults and juveniles can be significant, and its ultimate effect on future reproductive success, whether for first-time or repeat-spawning adults, has not been adequately measured or put into the context of population and genetic viability. At high-latitude locations, where the proportion of repeat spawners is high, the protection of postspawning adults becomes a high priority. In certain cases, the downstream passage of adults may be as important as or more important than the upstream passage in terms of the total reproductive potential for a particular watershed (Castro-Santos and Letcher 2010; Maltais et al. 2010).

The limitations in the performance of salmonid fishways and downstream passage structures are now being recognized in terms of their poor performance not only for American shad but also for other species. Although knowledge of the behavior of American shad has increased somewhat since the late 19th century, application of this knowledge to passage structure design has been slow and improving existing structures to accommodate American shad has been difficult, expensive, and often unproductive. A more effective scientific approach to improving passage for American shad would be to (1) understand and characterize shad behaviors on an experimental basis, especially with respect to attraction, swimming performance, schooling, and energetics; (2) design structures that capitalize on these behaviors to maximize passage efficiency and school integrity and minimize delays, injury, stress, and energy expenditure; and (3) validate structural performance in both controlled large-scale laboratory tests and at field test sites under a variety of site-scale, hydraulic, and environmental conditions. Efforts to expand knowledge and design application in this heuristic manner are probably the best long-term strategy for advancing passage technologies for American shad (and possibly other anadromous alosines) and eliminating the old paradigms of unpredictable behaviors and limitations to passage success for this species.

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