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RESEARCH

Considerations for Multi-Species Fish Passage in California: A Literature Review

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ABSTRACT

This review serves as a guide to improve multi-species fish passage. Human development along waterways in California during the last 160 years has adversely affected fish populations in many watersheds. Conflicts in water usage will only intensify with modern developments and population growth. Since most past fish-passage improvement efforts in California have focused on salmonids, I summarize the published studies and considerations that affect multi-species fish passage. To be effective, conditions in fishways need to meet the specific hydraulic requirements, as well as abilities, behavior, and size consideration for all fish species being considered. Turbulence, water depth, velocity, passage location, and design of a passage facility are essential elements to successful fish passage. Because of a lack of research on most of the native species, species-specific passage criteria are not fully defined, and it may be helpful to use data for physically similar, surrogate species found in similar habitats.

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KEY WORDS

Fish ladder, **fish** passage, lamprey, multi-species, native fish, passage behavior, shad, sturgeon, water turbulence, water velocity.

INTRODUCTION

Many fish species undertake extensive movements and depend on barrier-free streams to access adequate spawning habitats and maintain their distributions. Migration passage of anadromous or potamodromous fishes in most large and small rivers is impeded by a variety of modifications such as water-diversion structures, stream bed alterations, floodplain channelization, dams, and weirs (Rochard et al. 1990; Sheer and Steel 2006; Brown et al. 2013). Native fishes in California have experienced significant population declines that correlate to the degree of artificial modification of the waterway and passage impairments experienced over 150 years (Moyle 2002; Katopodis and Williams 2012). Habitat connectivity through improved fish passage is one important component of the conservation of stream-resident and anadromous fishes (Labbe and Fausch 2000; Dobbs et al. 2004; Jager et al. 2016).

Fish ladders in North America date back 200 years. Designs were developed to mimic conditions in which the fish were found. Most fish-passage facilities designed by state and federal agencies of the Pacific states and British Columbia, Canada, were designed for salmonid passage (see "Additional Resources") and have led to the development of five main types of fishways: pool-and-weir, baffle, vertical-slot, natural bypass, and fish elevators. Many variations of these types of structures have been built, many don't work as planned or limit passage of target species, and few have been planned or built to protect the diverse ecology of the stream (Brown 1991; DVWK 2002; Thiem et al. 2011).

Little is known about the behavior and passage needs of non-salmonid North American native fishes (Katopodis and Williams 2012). Fish ladders designed specifically for migrating salmonids may impede passage of other fish species (Katopodis and Williams 2012). For instance, 28.7% inclined Denil fishways 0.56 m wide and longer than 15 m at a flow of $0.16\,m^3\,s^{-1}$ impede the passage of American Shad *Alosa sapidissima* and Northern Pikeminnow *Ptychocheilus oregonensis* (Slatick and Basham 1985). Most fish-passage structures are ineffective for sturgeons and lampreys to pass through because of these species' sizes, behaviors, and physiologies (Daigle et al. 2005; Thiem et al. 2011; Goodman and Reid 2017; Katopodis et al. 2019).

The following summarizes the available data for two of the species groups thought to face the greatest passage challenges in the region: anadromous sturgeons and lampreys. I also examine other important non-salmonid fishes, the non-native anadromous American Shad *Alosa sapidissima* and native potamodromous fishes such as Sacramento Splittail *Pogonichthys macrolepidotus*, Sacramento Blackfish *Orthodon microlepidotus*, Sacramento Pikeminnow *Ptychocheilus grandis*, Sacramento Sucker *Catostomus occidentalis*, Hitch *Lavinia exilicauda*, and Hardhead Minnow *Mylopharodon conocephalus.*

The overall emphasis is on California's Central Valley watershed, the epicenter of many of the most serious resource-management issues in the region (Service 2007). Although I obtained substantial passage information from other geographical areas, the data should still be relevant to regional issues.

STURGEON

Most species (23 of 28) in the Order Acipenseriformes, to which sturgeons belong, are at risk of extinction (Birstein et al. 1997; Katopodis et al. 2019). Blocked migratory routes and reduced availability of spawning habitat are probably the greatest factors that contribute to the population declines of most sturgeon species (Auer 1996; Jager et al. 2016; Katopodis et al. 2019).

In the Pacific coastal waters from Mexico to Alaska, two species of sturgeon are found and both occur in California: White Sturgeon *Acipenser transmontanus* with populations declining (CDFG 2014), and the federally listed as threatened Green Sturgeon *Acipenser medirostris* southern distinct population segment (Fed Regist 2009).

Most adult sturgeons in a riverine environment tend to be strong swimmers and prefer deeper waters. As an example, adult Gulf Sturgeon *Acipenser oxyrinchus desotoi*, another riverine sturgeon that prefers swift waters for spawning, are found in waters with velocities near $2.5\ m\,s^{-1}$ (Cech and Doroshov 2004). Spawning White Sturgeon require deep areas in rivers with gravel or larger rocks along the bottom and swift water velocities of up to $2.8\,m\,s^{-1}$ (Parsley et al. 1993; McCabe and Tracy 1994; Moyle 2002), mean water-column velocities from $0.5\,m\,s^{-1}$ to $2.5\,m\,s^{-1}$ (Parsley et al. 1993), with near-bed laminar flow velocities averaging $1.7\,m\,s^{-1}$ (Perrin et al. 2003). Green Sturgeon need spawning pools with fast waters and eddy flows in depths greater than 3.0 m, and substrates ranging from clean coarse sand to bedrock (Moyle 2002).

Swimming Performance and Endurance

Warren and Beckman (1993) found that some White Sturgeon were able to use the fish ladders on the Columbia River that were designed for the smaller salmonids and had water velocities

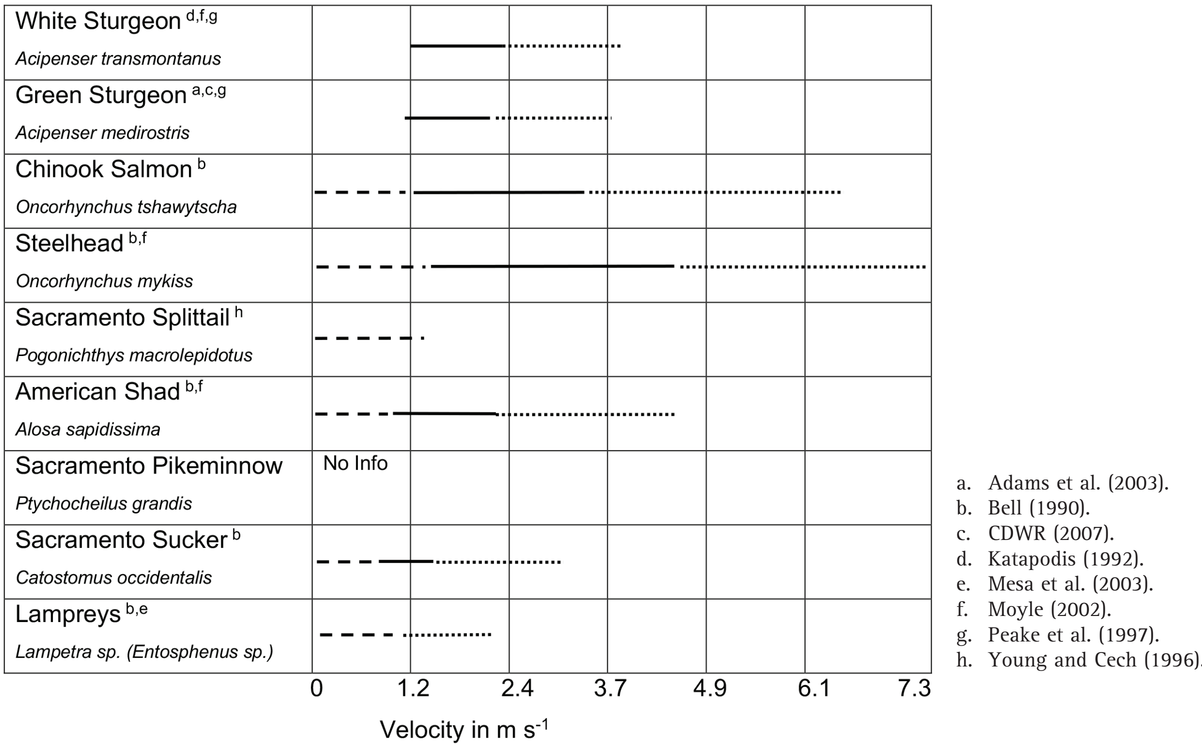

Figure 1 Relative swimming speeds of select California adult fishes
Bell's Table Classes Literature classes by Webb (1975) and Beamish (1978)
Cruising speeds ~ ('Sustained' for more than 200 minutes)
Sustained speeds ~ ('Prolonged' for more than 0.33 minutes)
Darting speeds ~ ('Burst' for less than 0.33 minutes)

of 2.4 m s^{-1} (Figure 1). This does not demonstrate that salmonid ladders are effective at passing sturgeon, just that individuals can ascend the ladders at those velocities. In reporting results of a metal flume study, Webber et al. (2007) suggest that for 2.0-m total length (TL) White Sturgeon adults, successful passage structures should incorporate rapid-velocity sections with flows of up to 2.52 m s^{-1} between somewhat slower sections of approximately 0.7 m s^{-1} for rest and recovery. That study was limited in its scope by its physical dimensions and a maximum velocity of 2.52 m s^{-1}.

Laboratory measurements of fish stress-related variables showed that adult White Sturgeon swimming 24 m against a current of 2.5 m s^{-1} physiologically recovered within 24 h (Cocherell et al. 2011), like the pattern shown in Rainbow Trout (Milligan and Wood 1986). A study with Rainbow Trout found that they recover faster when held at sustained swimming speeds of 0.9 body lengths per second (BL s^{-1}) compared to fish in still water (Milligan et al. 2000). This is equivalent to 1.2 m s^{-1} for smaller migrating White and Green Sturgeon. However, laboratory swimming tests may not be comparable to the more complex environmental conditions and behaviors observed in the field (Castro-Santos 2004).

White and Green Sturgeon are thought to have swimming performance comparable to other riverine sturgeon of the same size (Adams et al. 2003; CDWR 2007; Katopodis and Gervais 2016). Nonetheless, sturgeons were found to be one of the native riverine fishes to have the most difficulty ascending structures with high speed gradients and turbulent flows, even though the velocities do not exceed their capabilities (USFWS 1995). Migrating sturgeon are very large when compared to salmonids, with White

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Sturgeon reaching 3.2 m TL (Moyle 2002) and Green Sturgeon reported at 3.1 m TL (2013 email from M. Manuel, Pacific States Marine Fisheries Commission, to Z. Matica, unreferenced, see “Notes”); and are primarily a benthic-cruising “non-jumping” fish, so structures such as weirs or diversions, and fishways designed for salmonids, can impose significant constraints on sturgeon migration (Cech and Doroshov 2004; Webber et al. 2007).

As within most fish families (Figure 2), swimming speed and endurance in sturgeon generally increases with fish length (Wolter and Arlinghaus 2003; Katopodis and Gervais 2016). Although sturgeon have lower endurance when compared to salmon and trout of the same size, adult sturgeon are much larger and have comparable endurance at sustainable swimming velocities to adult salmonids (Katopodis 1992; Peake et al. 1997; Katopodis and Gervais 2016). Field studies with adult 1.2-m-fork length (FL) Lake Sturgeon *Acipenser fulvescens*, a weaker swimmer than similarly sized young adult White Sturgeon, were found to be capable of swimming 100 m against a current of 1.1 m s^{-1} and 6.0 m against a current of 1.5 m s^{-1} before needing a water velocity refuge (LeBreton 2004). Observations of radio-tagged White Sturgeon in San Francisco Bay by California’s Department of Fish and Wildlife (CDFG unpublished) and swimming performance studies in flumes have documented a sustained ability to swim against a 1.8 m s^{-1} current and short bursts of up to 2.4 m s^{-1} to 3.7 m s^{-1} (Katopodis 1992; Peake et al. 1997; Katopodis and Gervais 2016). In a laboratory flume, adult (1.5-m FL) White Sturgeon swam at 2.57 m s^{-1} for 20 m (Cocherell et al. 2011).

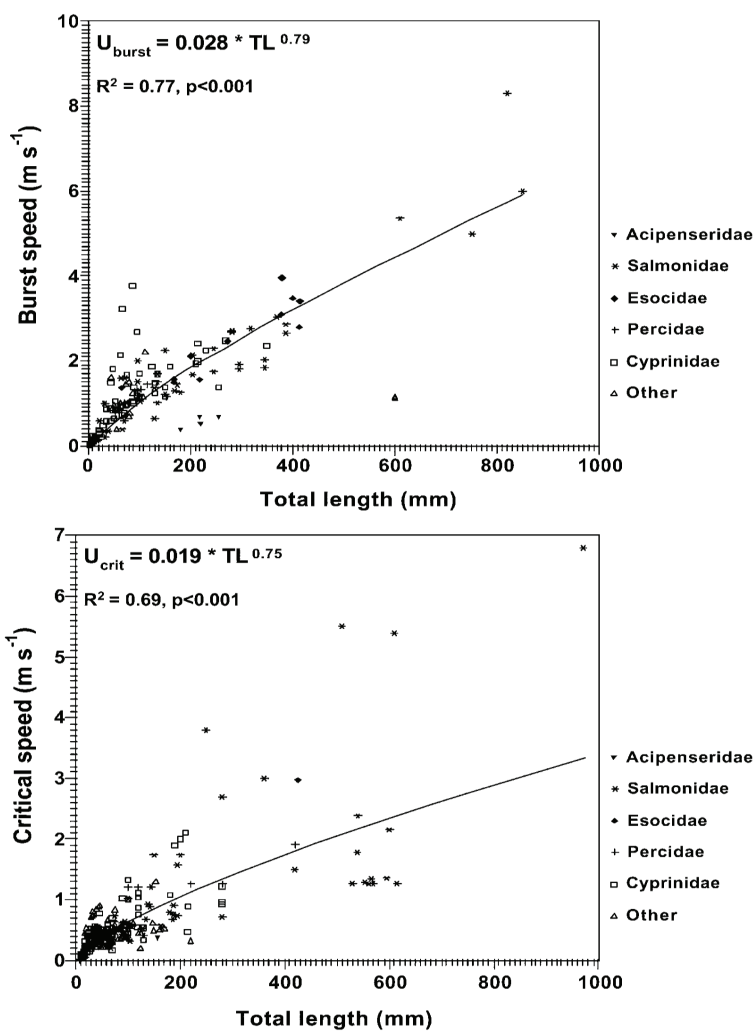

Figure 2 Models of burst speed and critical speed of fishes compiled from various studies. Source: Wolter and Arlinghaus (2003).

LAMPREY

All Pacific North American lamprey populations are spotty, in low numbers, and have been negatively affected by stream habitat degradation, water pollution, water diversions, water temperature increases, and migration impediments (Beamish 1980; Moyle et al. 2009). The US Fish and Wildlife Service (USFWS), in collaboration with Native American tribes and other federal, state, and local agencies, recognized the need for a comprehensive plan to conserve and restore Pacific Lamprey, by creating the Pacific Lamprey Conservation Initiative, with California a signatory.

Only Pacific Lamprey *Entosphenus tridentata* and River Lamprey *Lampetra ayresii* are anadromous in California and addressed in this report. Data suggest that these lampreys migrate in surges at night during elevated flows after a winter rain with a large spring run and a smaller fall run, and construct gravel nests at the head of riffles where water velocities are $0.2\,m\,s^{-1}$ to $0.85\,m\,s^{-1}$ and depths are 0.3 m to 1.5 m (Moyle et al. 2009). Little information is available on the River Lamprey.

Passage Observations from the Wild and Fishways

A key consideration for lamprey passage is their ability to squeeze through small spaces, ascend vertical or near-vertical structures by attaching to smooth surfaces, and their nocturnal lifestyle. The single most important factor that affects passage success appeared to be water velocity (Figure 1). While lampreys key in on some turbulence, they have difficulty negotiating fishways as a result of turbulence and water velocities that exceed $1.2\,m\,s^{-1}$ (Mesa et al. 2003; Moser et al. 2005; Kirk et al. 2017).

Entrances at the lower Columbia River dams, with approximately 0.46 m of hydraulic head, passed no more than 1 out of 10 lamprey successfully (Zobott et al. 2015). Decreasing the head level at the entrance to 0.152 m increased nighttime passage rates by 39%. Reducing flows at entrances produced the most notable improvement in lamprey movement (Katopodis and Gervais 2016). Clay (1995) found that velocities at fishway entrances usually approach or exceed $2.0\,m\,s^{-1}$, surpassing the swimming abilities of these fish. When confronted with high velocities, adults use their suctorial disc to hold fast to the substrate, surge forward, then reattach, and rest between intervals of burst swimming. This saltatory mode of movement is most pronounced in velocities greater than $0.6\,m\,s^{-1}$ (Daigle et al. 2005; Katopodis and Gervais 2016).

While rounding the entrance edges of structures to a minimum radius of 0.102 m significantly improved lamprey entrance efficiency, passage times, and passage by 30% (CRBLTW 2004), the addition of attachment plates in the transition area produced equivocal results (Daigle et al. 2005). Laboratory experiments indicated that attaching a 0.305-m-wide metal plate over the grating (diffuser plates) allowed lamprey to attach near, and pass through, an orifice opening with $> 2.4\,m\,s^{-1}$ velocity flow (Daigle et al. 2005; Figure 3). In a field study of a pool-and-weir fishway designed to pass lamprey, Ackerman et al. (2019) found that with rounded corners with a radius of 1.15 m, flush-mounted weir gates, chamfered corners, and flush orifices, passage efficiency ranged from 84% to 98%. Daigle et al. (2005) found that few lampreys passed a weir using the overflow section, although those that did so passed the weir more quickly, in 38 s, than those passing via submerged orifices, averaging 3 m 20 s (Figure 3). They also found that the presence of steps, seams, or other surface irregularities at the base of orifices inhibited passage.

Providing lower-velocity paths for passage appears to be beneficial for adult lampreys. For pool-and-weir type fishways, the addition of velocity refuges within orifices, by securing artificial rocks to the bottom, decreased the amount of time that lampreys took to pass through the orifice, and increased the proportion that made use of the orifice, although overall passage rate was unaffected by the addition of refuges (Daigle et al. 2005; Figure 3). Without refuges in place, 92% of lampreys passed all three of the Daigle et al. (2005) test weirs in 2-hour trials, and 66% of lampreys passed in 1-hour trials. Refuges at orifices reduced flows at the base of the orifice from about $2.0\,m\,s^{-1}$ to $1.0\,m\,s^{-1}$, allowing more fish to pass via the orifice.

Bunches of plastic bristles affixed to the base of the Isohaara fishway in the Kemijoki River in northern Finland were used to reduce velocities through the vertical-slot section (Laine 2001) and help the passage of European River Lamprey *L. fluviatilis*. Hard plastic bristles or natural or synthetic branches have also been used on sloped ramps to help catadromous eel migrate (Clay 1995). In these designs, the elvers undulated their way up the ramp in much the same way a snake would climb a slope.

Goodman and Reid (2017) found that improved pool-and-weir fishways provide a low passage

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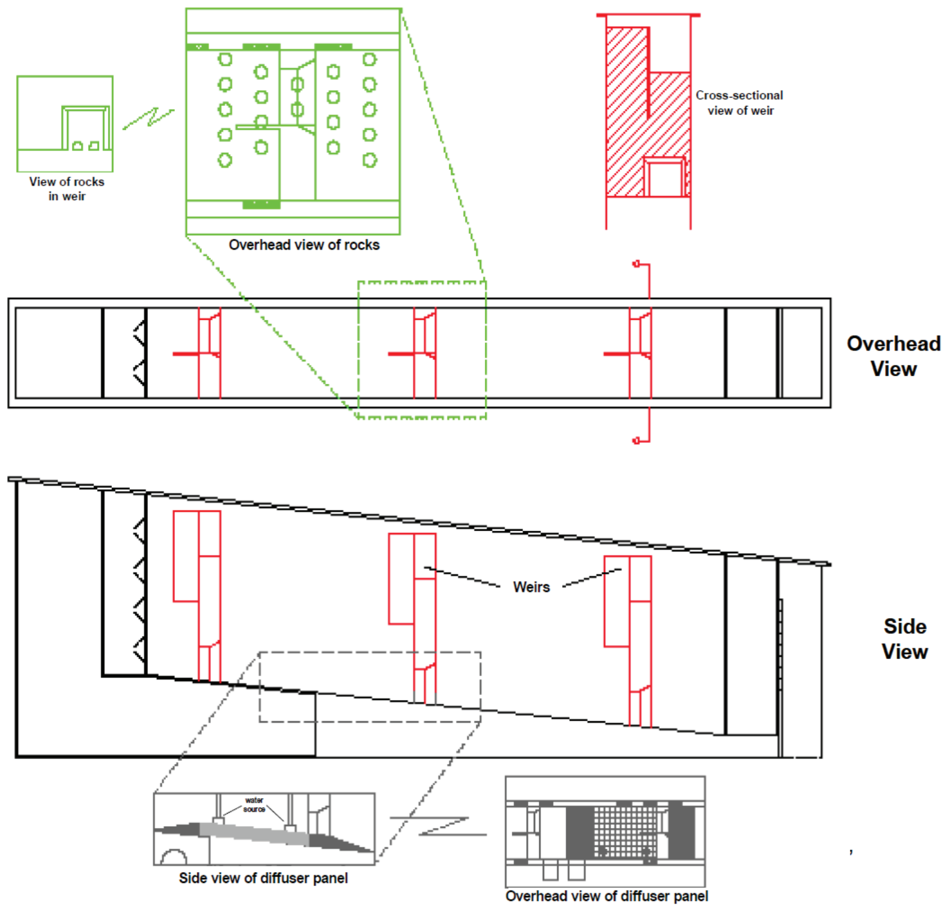

Figure 3 Diagram showing placement and structure of overflow weirs, orifices, a diffuser panel, and velocity refuges in an experimental pool-and-weir fishway. Source: Daigle et al. (2005).

efficiency at 44% with an average passage time of 5.2 h, while a lamprey passage structure (LPS) tube and culverts provided the highest efficiency, with average times of 0.26 h. Also, modifying a dam fishway with a variable-width weir and flow disruptors created velocity heterogeneity but did not improve passage, although installing an LPS saw a significant increase in lamprey passage success (Moser et al. 2019).

Swimming Performance and Endurance

Pacific lampreys have critical swimming speeds (Figure 1) of about 0.85 $m\,s^{-1}$ (Bell 1990; Mesa et al. 2003), and swimming speed is positively related to temperature (range 5 °C to 15 °C). For example, the maximum sustained swimming speed of adult Sea Lampreys *Petromyzon marinus* at 15 °C is about 0.35 $m\,s^{-1}$, but only 0.23 $m\,s^{-1}$ at 2 °C (Beamish 1974). A workshop report by T. McAuley (as cited in C. Katopodis et al. 1994) states that Sea Lamprey at 14 °C to 20 °C have a maximum sprint velocity of 4.0 $m\,s^{-1}$ with an endurance of 30 s at a water velocity of 1.6 $m\,s^{-1}$ (Figure 4), and that at 10 °C endurance was the inverse of the cube of swimming velocity. The endurance curve improves substantially as water temperatures increase. However, lamprey have limited endurance compared to teleost fishes (Katopodis and Gervais 2016).

AMERICAN SHAD

Shad, an introduced species, are included in this paper because they are a popular sport fish and are important as a food source to the recovery of sturgeon and salmon populations (Close et al.

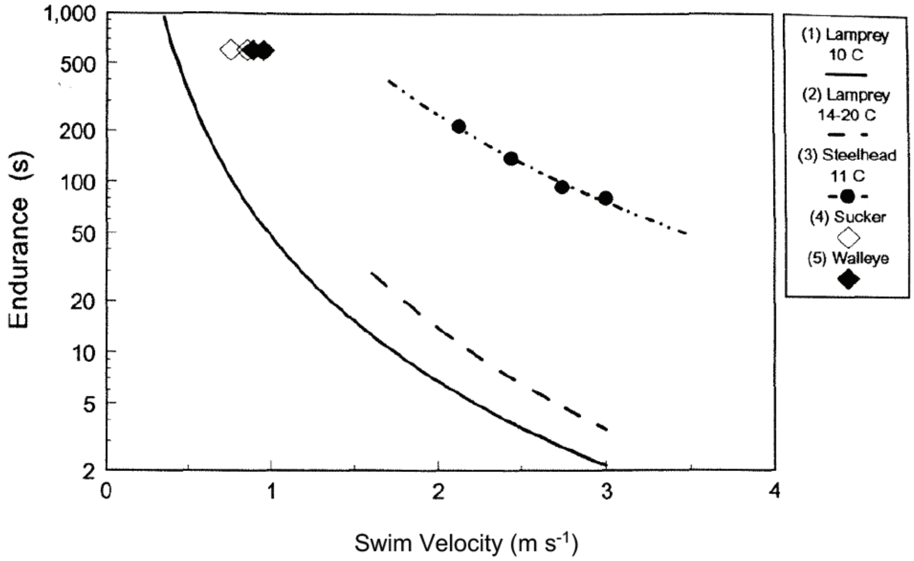

Figure 4 Comparison of swimming endurance of 45-cm-long Sea Lamprey to that of adult migratory fish common to the Great Lakes basin. Source: T. McAuley, as cited in Katopodis et al. (1994).

2002; UCWSRT 2002). Two species (Threadfin and American) are found in the northeastern Pacific from Canada to Mexico. This discussion focuses on American Shad *Alosa sapidissima* (Shad), introduced to California in 1871 and to the Columbia River in 1885, its population in decline for years (Lochet et al. 2009).

Shad are found from March through June, correlating to rises in temperatures and river outflows (Quinn and Adams 1996), in many of the streams and rivers that support anadromous fishes (Moyle 2002). Shad are relatively strong swimmers (Figure 1) and preferred spawning habitats deeper than 1.0 m and with velocities less than 1.0 m s^{-1}. However, Shad also ascend high-velocity shallow riffles with depths equal to their body depth (Haro et al. 2004).

Passage Observations from the Wild and Fishways

Because of their strong schooling behavior, Shad are reluctant to separate at structures or in high-velocity zones (Larinier and Travade 2002). Shad do not leap when ascending water drops, but instead sprint through in the upper water column (Larinier and Travade 2002; Haro et al. 2012).

Shad have difficulty ascending fish ladders and may be stopped by even a relatively low dam with a fish ladder (CDFG 2007). In observations on the Columbia River, Shad were found to be reluctant to enter submerged orifices in a fishway (Monk et al. 1989). Unlike salmonids, Shad and most other species have much more difficulty in dealing with the helical current patterns inside baffled fishways (Larinier and Travade 2002) and prefer laminar or streaming flows. They mostly avoid flows with significant turbulence, air entrainment, hydraulic jumps, and upwelling (Larinier and Travade 2002).

Shad do attempt passage through existing fish ladders, but the duration of passage is highly variable and can affect survival (Lochet et al. 2009). On the Columbia River, Shad can pass through Denil fishways up to 11.9 m long (Slatick and Basham 1985), but stop in longer fishways, in holding ponds, and at fishway turns (Haro et al. 2012). Passage success rates at most fish-passage structures are low (Lochet et al. 2009; Haro et al. 2012). Modifications to fishways on the Columbia River with partial-width overflow slots and/or partial-depth side slots greatly improved Shad

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passage and benefitted salmonid passage (Monke et al. 1989; Petersen et al. 2003).

Swimming Performance and Endurance

In an open-channel flume study, 86% of Shad in the staging area entered the flume when the velocity was $1.74\,\mathrm{m\,s^{-1}}$, and 71% entered when the velocity was $3.43\,\mathrm{m\,s^{-1}}$ (Haro et al. 2012). Shad can swim at burst speeds of up to $20\,\mathrm{BL\,s^{-1}}$ for 4.5 s (Castro–Santos 2005; Katopodis and Gervais 2016), exceeding the burst speed, relative to body length, of salmon. In laboratory open-channel flume studies with very little turbulence, Haro et al. (2004) found that Shad can sustain a velocity of $4.5\,\mathrm{m\,s^{-1}}$ for approximately 5 m. Weaver (1965) found they can sustain $4.15\,\mathrm{m\,s^{-1}}$ for 6.1 m, and $3.47\,\mathrm{m\,s^{-1}}$ for 19.8 m.

SACRAMENTO SPLITTAIL

Only one species of splittail minnows is in California; the potamodromous Sacramento Splittail *Pogonichthys macrolepidotus* (Splittail). It is endemic to the low-elevation river channels below valley rim dams of the Central Valley and San Francisco Bay (Young and Cech 1996; Sommer et al. 2008). Splittail, in a long-term decline (Moyle 2004), was listed as threatened in 1999, but the USFWS remanded this in 2003 as a result of improved information about the species (Fed Regist 2003; Sommer et al. 2007).

Most Splittail migrate upstream between January and March during high flow events (Moyle et al. 2004; Sommer et al. 2014). Field studies suggest that they prefer shallow water habitats of 0.9 m to 6.7 m deep (Meng and Moyle 1995; Sommer et al. 2002; Sommer et al. 2008).

Swimming Performance

Splittail are strong swimmers but it is unclear if they can effectively use existing salmonid fishways (Moyle et al. 1995). The critical swimming velocity of adults (Figure 1) is interpolated from the literature at up to $1.37\,\mathrm{m\,s^{-1}}$ ($3\,\mathrm{BL\,s^{-1}}$) (Young and Cech 1996). Danley et al. (2002) measured Splittail (age-0, 4-cm to 7-cm standard length) swimming velocities of up to $0.523\,\mathrm{m\,s^{-1}}$ in a laboratory flume. Young and Cech (1996) also report that they can tolerate holding velocities of $0.305\,\mathrm{m\,s^{-1}}$ to $0.913\,\mathrm{m\,s^{-1}}$ in laboratory conditions. No literature was found that defined Splittail's prolonged swimming interval, burst swimming limit, or endurance criteria.

OTHER NATIVE FISHES

Although there are no published studies on swimming or passage performance for other adult native minnows (Hardhead, Hitch, and Sacramento Pikeminnow), some patterns can be inferred from anecdotal information, observations by the author, assumptions from surrogate data, and from physiological studies on juveniles. In natural conditions, Hardhead and Sacramento Pikeminnow are commonly observed swimming near the bottom alongside salmonids and prefer the swifter waters of riffles and the glides at the tail end of pools (personal observation). Waters in these areas are typically in the 0.6-m-s^{-1} to 1.2-m-s^{-1} range. Katopodis (1992) noted that swimming performance is generally similar across species relative to size, when fish are grouped by swimming physiology (Katopodis and Gervais 2016). Limited information is available on the Sacramento Sucker, generally found in slower waters than the Sacramento Pikeminnow (Figure 1) and could suggest that the Sacramento Pikeminnow has higher critical and sustained speeds. These minnows and the Sacramento Sucker have been observed darting upstream away from disturbances, and have been documented swimming up moderately inclined Denil fish ladders up to 15.2 m long (Slatick and Basham 1985). Myrick and Cech (2000) found that 0.2 m to 0.3 m Hardhead, Hitch, Sacramento Pikeminnow, and Sacramento Sucker had similar swimming performance at select temperatures, and that Hitch were significantly (11%) faster at higher temperatures.

Some inferences can be made based on size or taxonomic group. For example, Wolter and Arlinghaus (2003) compiled a model using data from several studies, and compared critical and burst speeds to body length (Figure 2). The model generalizes performance within a family of fish relative to body shapes and sizes. The families represented in their model include Acipenseridae (sturgeon), Salmonidae (salmon and trout), Esocidae (pikes), Percidae (perches), and Cyprinidae (minnows). Katopodis and Gervais (2016) use fish length, speed, and endurance to derive generalized curves. Some of the species groups are the same between Wolter and Arlinghaus (2003) and Katopodis and Gervais (2016). Estimates of speed and endurance for all species from Katopodis and Gervais (2016) can be made through Swim Performance Online Tools (SPOT; see "Additional Resources"). Using the performance values of the modeled families, the models can be used here to allow predictions for local fishes that represent, respectively, the following Central Valley species: Green and White Sturgeon, Chinook Salmon and Steelhead, Sacramento Pikeminnow and Hardhead, Blackfish and Sacramento Splittail, and the Sacramento Sucker. From this graph, inferences can be made on the swimming capabilities of represented adults that are longer than those depicted in the graph, such as adult White and Green sturgeon.

ADDITIONAL CONSIDERATIONS FOR PASSAGE CRITERIA

Designing fish-passage structures to meet several species' behavioral needs, as well as the largest fish and the weakest swimmers, will improve passage success for a wider variety of species, as is being considered in the San Joaquin River restoration project (Table 1). The historically narrow focus on salmonid passage has not been effective for other species. On the Columbia River, a 1938 passage elevator designed to help adult salmon get past a dam was found to be ineffective for this purpose and was decommissioned in 1971, even though it was very successful at passing sturgeon (Warren and Beckman 1993). Designing a traditional fishway to effectively and equally accommodate sturgeons, lampreys, salmonids, shads and other natives may not be feasible at some sites (Daigle et al. 2005). Well-designed Denil-type fishways (Figure 5) can pass salmonids and a few other species, but not most native fish species (Slatick and Basham 1985; Katopodis et al. 1991). Extensive modifications created the Ice Harbor Fishway design (Figure 6) with a partial-depth side slot to improve overflows that resulted in greatly improved Shad passage and some improvement to salmon passage (Monk et al. 1989; Petersen et al. 2003). Although challenging to design fishways for multiple species, recent research provides optimism that knowledge, experimental and field studies, computational tools (e.g., computational fluid dynamics [CFD] software), and data-based swimming performance curves for many species are better now than 10 or 30 years ago (Katopodis and Williams 2012; Silva et al. 2012; Katopodis Ecohydraulics Ltd. 2013; Marriner et al. 2016; Amaral et al. 2018; Katopodis et al. 2019; Quaranta et al. 2019).

Multi-Path Considerations

A primary challenge in developing an effective fishway is how to separate lamprey from other species if the LPS is independent of the primary fish passage structure. Some options are to develop a passageway within a fishway to help lamprey and/or other non-salmonids pass. A fishway can be designed as an asymmetrical passage structure with reduced turbulence and partial baffles on one side; or by adding an LPS tube (Figure 7), a culvert; or constructing a parallel passageway that provides the complexity of natural riverine channels (Wildman et al. 2005; Goodman and Reid 2017).

Passage slot size and location, maximum velocities, baffling for velocity refuges, conditions of turbulence, and surface features of fish passage structures need to consider all the species that require passage, (e.g., appropriately modified fish ladders may increase the passage success of many species [DVWK 2002]).

Behavioral Issues

Fish-passage design criteria must allow for the behavioral needs of each species. Long baffled fishways and fish ladders with turning basins (switchbacks) can significantly reduce passage efficiency for some species, including shad and sturgeon (Thiem et al. 2011; Haro et al. 2012). Many species have difficulty in dealing with the helical current patterns associated with the baffles and orifices found in most fishways.

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Table 1 San Joaquin River Restoration Project native fish attributes table. Source: SJRRP Fish Management Work Group. Source: SJRRP Native Fish Attributes Table, revised May 14, 2013. *http://restoresjr.net/*

Species	Migration time	Life stage and direction (primary/ secondary)	Desired migration frequency by Water Year type	Min depth of flow (m)[a]	Jump (Y/N)	Max fish jump height (m)	Recommended structure jump Height (m)	Cruising speed[b] (m s−1)	Sustained speed[b] (m s−1) (max sustained)	Burst speed[b] (m s−1)	Non-leaping passage	Recommended design velocity (m s−1)m
Pacific Lamprey	Mar-Jun (primary)[s] Aug-Oct (secondary)	adult US ammocetes DS	all except CL[n]	0.30	N (but can climb)	n/a	n/a		0.46[p]	0.86[p]	wetted ramp rounded corners[q]	0.85
White or Green[c] Sturgeon	Mar-Apr (primary)[s] Feb-May (fringe)	Adult (US/DS) juvenile DS	NW and W only	1.00[d]	N	n/a	n/a		1.23–2.26[e]		swim through	2.01
Central Valley Steelhead	Oct-March (adult) Oct-May (juvenile)	adult (US/DS) juvenile DS	all except CL[n]	0.37	Y	2.44–3.66[f]	0.46[g]	1.04	4.18	8.08	n/a	0.46–1.22
Chinook Salmon (adult)	Mar-May (spring run) Oct-Dec (fall run)	adult US	all except CL[n]	0.37	Y	2.13[f]	0.46[g]	1.04	3.12	6.83	n/a	0.46–1.22
Chinook Salmon (juvenile)	Nov-May	juvenile (DS/US)	all except CL[n]	0.30	Y	0.21 for 45–65 mm 0.30 for 80–100 mm[g]	0.15	0-0.46	0.76	1.52	swim through	0.91[g]
Sacramento Pikeminnow[h]	Mar–May (primary)[o] Aug–Oct (secondary)	adult (US/DS) juvenile (US/DS)	W, NW, ND[q] (approx. 2 of 3 yrs)	0.30	Y	Probably 0.61[i]	n/a		0.39	0.78	swim through	0.76
Hardhead[h]	Apr–May (primary) Jun–Aug (fringe)	adult (US/DS) juvenile (DS/US)	W, NW, ND[q] (approx. 2 of 3 yrs)	0.30	Y	Probably 0.61[i]	n/a		0.47	0.94	swim through	0.91
Hitch[h]	February–March	adult (US/DS) juvenile DS	W, NW, ND[q] (approx. 2 of 3 yrs)	0.30	Y	Probably 0.30–0.46[i]	n/a		0.39	0.78	swim through	0.76
Sacramento Splittail[k]	Jan–Feb (primary)[o] Mar, Apr (fringe)	adult (US/DS) juvenile DS	W, NW, ND[q] (approx. 2 of 3 yrs)	0.30	Unknown	Unknown	n/a		0.66	1.33	swim through	1.31
Sacramento Sucker[h]	Jan–Feb (primary)[o] Dec, Mar, Apr (fringe)	adult (US/DS) juvenile (DS/US)	W, NW, ND[q] (approx. 2 of 3 yrs)	0.30	Y	Unknown	n/a		0.47	0.94	swim through	0.91
Sacramento Blackfish[j]	Mar-Jul[o]	adult (US/DS) juvenile (DS/US)	—[l]	0.30	Unknown	Unknown			0.51	1.02	swim through	
Kern Brook Lamprey	not applicable to Reach 2B											
California Roach	spring	adult (US/DS) juvenile (US/DS)	—[l]	0.30	Y	Unknown		Unknown	Unknown	Unknown		
Tule Perch			—[l]	0.30	N	Unknown		0.06	0.19	0.39	swim through	
Prickly Sculpin	not applicable to reach 2B			0.30	N	n/a						
Riffle Sculpin	not applicable to reach 2B			0.30	N	n/a			0.77	0.77		

Legend:	not used for design criteria	US adult salmon design criteria	US juvenile salmon design criteria	US native fish design criteria

Table 1 Notes

a. Based on 1.5 times body depth or 1-foot depth, whichever is greater, unless otherwise noted.
b. Calculated from Bell (1990) from relationship on page 6.2 unless otherwise noted: Cruising speed = 1/6 V_{max}, Sustained swimming speed = 1/2 V_{max} relative to Burst or Darting speed (V_{max})
c. White Sturgeon were considered a valid surrogate for Green Sturgeon for the purposes of determining swimming performance (CDWR 2007).
d. CDWR 2007; Webber et al. 2007, Recommended velocities are: U/S movement: 2.03–2.54 $m\,s^{-1}$, resting: 0.51–0.68 $m\,s^{-1}$
e. Adams et al. 2003.
f. Bjornn and Reiser (1991).
g. NMFS (2008). Recommended velocities for Columbia and Snake River Fish Passage Facilities for upstream passage of juvenile salmon:
0.46–0.76 $m\,s^{-1}$ for 46–65 mm juveniles, 0.91–1.37 $m\,s^{-1}$ for 80–100 mm.
h. Myrick and Cech (2000).
i. Based on field observations by T. L. Taylor or L. Wise.
j. Inferred from Myrick and Cech (2000).
k. Young and Cech 1996.
l. Non-migratory behavior for spawning, but will utilize high flow connectivity.
m. Recommended average maximum velocities for fish passage facilities.
n. Every year except Critical Low water years.
o. Workman (2001).
p. Moser and Mesa (2009).
q. USFWS (2010).
r. Wet, Normal Wet, and Normal Dry years.
s. Harrell and Sommer (2003); Webber et al. (2007).

Studies on the Columbia River at the dam fish-passage facilities found that shad avoided passing through the submerged orifices in the fish-ladder baffles. Also, it should be noted that some species are documented as avoiding longer culverts (a dark tube). Passage performance of native fishes under these conditions is less well understood.

Substrates and Surface Features

Substrates are more significant to bottom fishes than to midwater fishes. A passage channel with anchored rounded baffles (Figure 3), such as boulders, could increase sturgeon passage success. Adult sturgeon can more easily pass rock ramps with scattered boulders than ladders with vertical or horizontal baffles (White and Mefford 2002).

Lampreys, the weakest swimmer reviewed (Figures 1 and 4), typically swim up high-velocity corridors by using their oral discs to attach to suitable substrates in a burst-and-attach behavior. Lamprey-friendly structures need adequate smooth anchorage surfaces and rounded edges with a radius of no less than 0.15 m, to allow them to use their unique burst-and-attach behavior (USFWS 2014; Ackerman et al. 2019). Lampreys are most vulnerable in the time between successive attachments.

Velocity and Fatigue

The velocity-limiting factor in a multi-species fish-passage structure is defined by the smaller, weaker swimmers. For fish facility structures to effectively pass lampreys they need to provide low turbulence and passage velocities < 1.4 $m\,s^{-1}$. The distance through a structure, or from velocity refuge to refuge, and the turbulence and size of eddies compared to fish length, are important factors that affect passage success (Table 2 in CDFG 1998; Silva et al. 2012). Even with velocity refuges, successive exposure of a species to peak performance conditions creates accumulative fatigue (Silva et al. 2012). Passage studies in tightly controlled laboratory swimming tests may not directly compare to the more complex environmental conditions and behaviors observed in the field (Castro-Santos 2004). Models presented by Bell (1990) and Clay (1995) are based on the assumptions that fish would swim at near-maximal speeds, fish will swim to fatigue, and that interspecific and intraspecific variation is negligible. This is never true in nature, and it prompted research to develop fish performance models based on distance traversed (Weaver 1965; Castro–Santos 2002; Haro et al. 2004; Katopodis and Gervais 2016) and on swim speed-fatigue time relationships that allow for variations in water velocities and fish swimming speeds (Castro–Santos 2006; Katopodis and Gervais 2016).

Water Depths

For sturgeon, water depth along the passageway needs to be at least 0.6 m, and depths > 0.9 m are preferred. Sturgeons during migrations were observed passing over shallow riffles of 0.6 m on the Yuba River in California (2012 in-person conversation between A. Seesholtz, CDWR, and Z. Matica, unreferenced, see "Notes").

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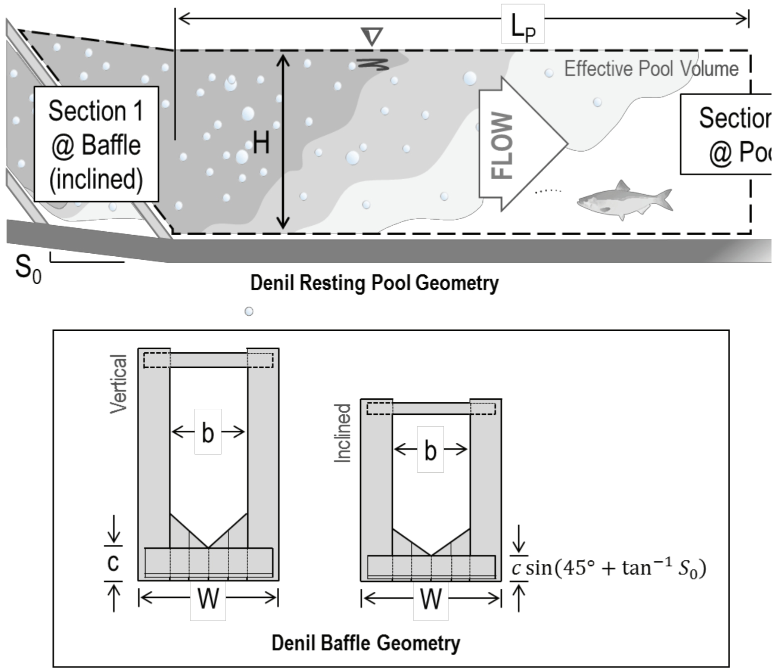
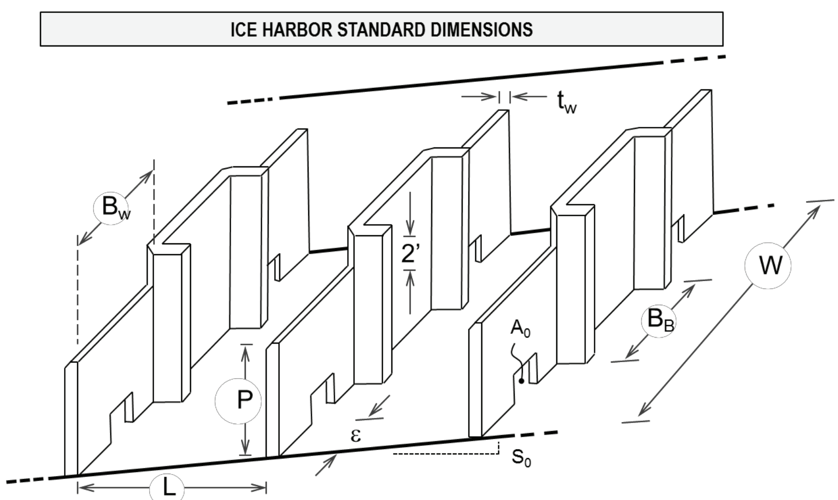


Figure 5 A cross-section view of a Denil fishway resting pool and baffle. Source: USFWS (2017).



$$L \geq 9\,ft \qquad S_0 \leq \frac{1}{10} \qquad B_B = 0.375W \qquad B_W = 0.625\frac{W}{2}$$

Figure 6 Ice Harbor fishway standard dimensions, where B_W is the overflow weir crest width, B_B is the non-overflow baffle width, A_0 is the area of the orifice opening, S_0 is the floor slope, L is the pool length, W is the pool width, P is the overflow weir crest height, t_W is the overflow weir crest thickness, and ε is the distance from the center of the orifice to the side wall. Source: USFWS (2017).

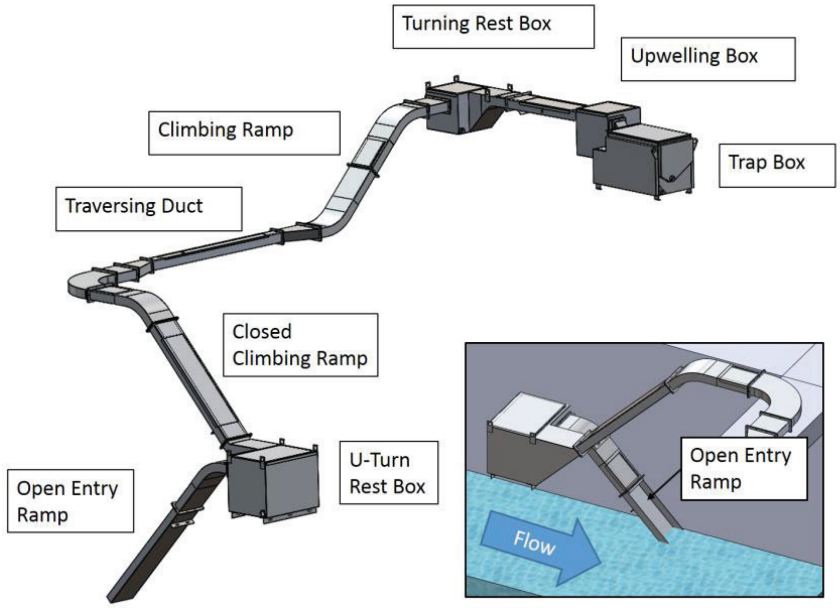


Figure 7 Schematic of typical LPS major components and parts. *Source: Zobott et al.(2015).*

For fish not well studied, using data from field observations and generalizations can provide some design considerations (Katopodis and Gervais 2016). For Shad, the preferred spawning habitat is > 1.0 m deep, but Shad are also seen ascending high-velocity shallow riffles with depths equal to their body depth (Haro et al. 2004), indicating that they can pass through structures where the water depth is < 1.0 m.

Fish Size

Most fish ladders are designed to accommodate salmonid-sized fishes, not the larger sizes of adult sturgeons. Warren and Beckman (1993) state that the typical length of sturgeon that use existing fish ladders is 0.5 m to 1.2 m, and that larger sturgeon would have difficulty negotiating the orifices of fishways on the Columbia River. Scaled-up structures would improve sturgeon passage.

RECOMMENDATIONS

The minimum length of a fish-passage structure is dictated by the necessary elevation change at the site and by the specifics of the ladder type chosen. So, high-head dams may compound physiology- and behavior-inhibiting effects with some species. The primary parameters in the design of a -species fish-passage structure through a low-head control weir will be velocity, field and intensity of turbulence, adequacy of substrate and side surfaces, and the design, spacing, and placement of velocity reduction baffles.

Considerations for multi-species fish-passageway design should include the following:

- Mimic natural channels.
- Minimize turbulence at water entrance and exit flows.
- Reduce helical current patterns inside baffled fishways.
- Scale turbulence and size of eddies to body lengths.
- Ensure side surfaces are smooth and regular and provide an open pathway to pass lampreys.

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- Ensure bottom surfaces are smooth and regular, or have hemispherical baffles, so as not to obstruct lamprey and sturgeon passage.
- Ensure bottom passage through or around baffles are a minimum of 0.75 m wide and 0.6 m high to accommodate large sturgeon.
- Ensure attraction water velocities are between 0.3 $m\,s^{-1}$ and 0.9 $m\,s^{-1}$.
- Create, via baffling, slow-velocity zones of 0.6 $m\,s^{-1}$ to allow smaller and weaker fishes to rest and recover.
- Keep velocities to less than 2.3 $m\,s^{-1}$ to optimize sturgeon passage, or, more conservatively 1.5 $m\,s^{-1}$, to increase the success of smaller sturgeon and lamprey passing. The critical swimming speed of lamprey suggests a velocity maximum of 1.4 $m\,s^{-1}$, but with low turbulence, a clear passageway, and smooth anchoring surfaces, lamprey can handle velocities of up to 2.0 $m\,s^{-1}$.
- Offset orifices to provide the highest rates of passage in the corresponding lowest times.
- Reduce Reynolds shear with offset and straight orifices to improve fish transit times.
- Use a deflector bar arrangement to reduce eddies found in straight orifices to similar in size to a fish's length (Silva et al. 2012).
- Align (do not offset) baffles, which offer velocity refuges, to allow straight swimming paths of >0.6 m widths (Webber et al. 2007), and space them a minimum of 1.5BL, or 4.5 m and a maximum of 5.5 m to accommodate large and small fishes. As a reference, the minimum baffle spacing for Chinook Salmon to pass in a pool-vertical slot fishway is 1.5BL or 1.5 m.
- Keep unbaffled velocities to less than 1.8 $m\,s^{-1}$, to pass smaller sturgeon when present.
- Velocity refuges should provide velocities in the sustained velocity range of a species. Webber et al. (2007), suggests a velocity of 0.68 $m\,s^{-1}$ for rest and recovery for White Sturgeon. That appears to be overly conservative, but lamprey would benefit from refuge velocities near 1.0 $m\,s^{-1}$ (Daigle et al. 2005).
- Keep water depth > 1.0 m to facilitate sturgeon and shad passage.
- Construct fish ladders without turning basins (Thiem et al. 2011).
- Round the corners of edges and transition angles with a radius of at least 0.15 m to improve lamprey passage efficiency (CRBLTW 2004; Ackerman et al. 2019).
- Fasten plastic bristles into the bottom of vertical slots (Laine et al. 1998) to help lampreys pass.
- Provide alternate passage routes, such as LPSs, for lamprey (Goodman and Reid 2017; Moser et al. 2019) (Figure 7).

A design option that could meet these conditions would need to be more complex than current designs, and may have multiple channels to pass water and fish along its sides, the bottom, and through overtopping slots with reduced turbulence. For fish to transition to and beyond the facility, passage channels should have extended flared approach and departure zones to dissipate energy, reducing velocities and turbulence. Passage channels for multiple -species that need velocity-reduction devices (baffles) should have movable baffles and adequate anchor points (bolt sites) built into the channels' surfaces. The spacing, size, and shape of these devices could be altered to enhance the passage of any of the target species and fine-tune a structure to the species and the site. Channels could have a portion of their widths free of obstacles that create turbulence, as well as have turbulence-dampening structures, large bottom and side orifices, and overflow slots, to allow lamprey, shad, and sturgeon to pass.

The literature presented here underscores the lack of data and the uncertainty of how to best improve multi-species fish passage. Because fish-passage data are limited or lacking for many species, and their status as species of concern may limit availability of some for study, generalizations and appropriate surrogate species may need to be considered (Cahoon et al. 2005; USFWS 2014; Katopodis and Gervais 2016). Swimming performance tends to be generally similar across species with similar life histories when grouped, relative to their size, by swimming physiology (Katopodis 1992; Katopodis and Gervais 2016). Additional studies, and analysis of successful structures and of the modifications to existing fishways, are needed to improve confidence and success in future designs or modifications of multi-species fish-passage structures.

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ADDITIONAL RESOURCES

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