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Technical Fishway Limitations and Common Misconceptions

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ABSTRACT

Man-made barriers have resulted in a decline in migratory fish species populations by reducing the geographical range of migration, limiting access to necessary habitat including spawning grounds and nursery rearing areas, impacting species life cycles and ecosystems, ultimately resulting in an overall decrease in species biodiversity. Fishways generally allow fish to maintain, extend, or even re-establish migrations over both man-made and natural barriers. Fishways, used in both upstream and downstream lotic environments, are generally classified as either technical or nature-like and are designed to provide aquatic ecosystem sustainability and river connectivity worldwide. In the case of upstream technical fishways (i.e., fish ladder), when appropriately designed and situated, fish ladders allow upstream migrating fish to bypass river barriers to reach river segments suitable for growth and reproduction. While a common method of providing passage in many systems, fish ladders can present biological and engineering challenges and limitations. Importantly, there are common misconceptions related to fish ladders as well as uncertainty regarding their appropriateness as the only perceived solution to a fish barrier. This paper explores and presents some of the shortcoming of fish ladders, and more specifically upstream technical fish ladders, and highlights design elements to consider for providing the highest degree of fish passage efficiency.

Keywords: Upstream technical fish ladder; Physical barriers; Flow-fish interactions; Efficiency; Entrance condition; Auxiliary water supply; Fall back

INTRODUCTION

Upstream technical fish ladders have been providing successful fish passage solutions for over three centuries and are often thought of as the only solution to providing river connectivity and passage to a multitude of diadromous and resident fish species. In reality, fish ladders are generally designed and sized to provide optimum conditions to support upstream passage to specific target fish species and, importantly, may only provide upstream passage during certain periods of time. In North America and Canada, fish ladders routinely target anadromous species ("upward-running" species) that have hatched in freshwater, matured in the ocean, and are migrating back up rivers to continue their life cycle. Common examples of anadromous fish in North America are several genera and multiple species in the Salmonidae family. While commonly designed and operated for commercially-important anadromous salmonids, upstream technical fish ladders are often not the preferred passage solution for all fish species and catadromous fish such as eels and resident fish (weaker swimmers) are often neglected from design and operational considerations. In addition to limiting or preventing passage of all fish species, fishways do not always work properly over all flow regimes, and may not be well operated or maintained. To illustrate, Herman Wanningen, founder of World Fish Migration Foundation, recently presented a figure during the future of river connectivity conference in Africa (March 5, 2021) suggesting that only about 30% of the fishways in the Netherlands work well; the keys here is that 70% of the fishways do not work well and leads one to questions whether or not effective fish passage systems worldwide may be operating at similarly-poor rates. This paper explores and presents some of the misconceptions and misapplication of upstream fish passage systems to better-inform owners and designers alike of specific design and operational items to consider when working with similar systems. The objective of this paper is to provide a clear understanding of fish

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ladders so that the community of owners, designers, and permitting agencies can develop meaningful improvements to both current and future to technical fish ladders.

TECHNICAL FISHWAY OVER VIEW

Technical fishways work by breaking down the overall hydraulic head (difference in water level upstream and downstream of the barrier) into a series of small and manageable "steps" that dissipate energy and provide navigable conditions for fish to pass otherwise impassable barriers. Successful technical fish ladders are best developed using a combination of biological knowledge and experience, research, and engineering; these practices combine specific skills and knowledge to produce a single structure with the ultimate measure of success being the degree of passability to migrating fish species. The following paragraphs present areas of common misconceptions, errors, or simply elements to be considered prior to designing a technical fish ladder.

WHAT ARE SOME OF THE MISCONCEPTIONS OF FISH PASSAGE?

This section explores some of the most common misconceptions regarding Fish Passage (FP) systems. While many of these concepts and concerns are commonly-known for people in the fish passage field, they are not always clear to hydropower facility owners who, through re-licensing and regulatory mandates, are sometimes forced to provide passage to fish but know little about the subject at the onset of the project. It is important to educate a wide range of stakeholders so that the goals and requirements established at the beginning of the project, during an alternative evaluation or conceptual design, are clear and well-defined goals and requirements understood by all.

FP systems work all the time

The first misconception is that fish ladders work and are operating all the time; this is an important misconception that is not always true. Fish Passage systems can operate seasonally, when target fish species are migrating, and be either off-line the rest of the time or work at reduced efficiency. Establishing clear expectations around the non-migratory period can be as important as during the migratory season.

Design guidance materials inform the design engineer that fish passage shall operate within specified design criteria between a low and high stream flow. Within this range of stream flow, the fishway shall allow for safe, timely, and efficient fish passage when properly designed. In the United States, the design low flow is generally defined as the mean daily average stream flow that is exceeded 95% of the time during periods when migrating fish are normally present at the site and typically calculated using the previous 25 years of flow data during the fish passage season. Similarly, the design high flow is the mean daily average stream flow that is exceeded 5% of the time. However, outside of the bracketed "5% and 95%" values, there are some misconceptions and assumptions that often vary between stakeholders. An obvious assumption related to the development of flow ranges exists with not always being able to accurately predict future flow ranges based on historic data, especially given the recent extreme variances in global climate change; use of mean historic flow data could lead to extreme under- and/or over estimates of the design flow range in rapidly changing climates.

Design within the 5% and 95% flow range importantly neglects the reality that systems will often operate outside of the design flow range. While passage concerns for operation outside of the target flow range may exist, these concerns are often perceived differently by the various stakeholders, with biological, engineering, permitting, or financial variables playing a major role in identifying the importance (or lack of) of these events. Common design guidance materials state that "outside of this flow range, fish must either not be present or not be actively migrating or must be able to pass safely without the need of a fish passage facility" [1]. Taking the case of fish not being present, one may assume that the fishway may be turned off (e.g., to save pumping cost or operational cost) or that the ladder would still be operating but less efficiently to provide passage to resident fish.

Independent of flow ranges, it is also important for stakeholders to have a solid understanding of the fish passage "window" (period) for a planned system. The fish passage window identifies when certain fish species will be present at a given location. Fish passage windows are generally developed and focused on one or more targeted fish species and rarely addresses the full complement of species (and life stages) present in the aquatic system. Linked closely to identifying a fish passage window, there is a general assumption that sound and available information exists relating to the number and timing of fish returning per season. When considering new fish passage systems, this assumption is not often the case and rather than taking the time to gather site-specific information over multiple seasons, projects may be rushed, and assumptions made based on general fish migration windows which may or may not be directly applicable to the site.

A thorough understanding and dialogue of these topics, including stakeholder expectations associated with each, in advance of the final design is critical. Poorly understood or misinterpreted project goals and design criteria can lead to a perception that the fish ladder is "not functioning."

FP systems pass all fish

Another misconception is that fish ladders pass all types of fish all the time. Historically, fish ladders were designed to accommodate culturally significant and economical species, such as salmon, shad, and sturgeon Fishways are therefore often designed around target species and many times these species are selected because of regulatory status (e.g., U.S. Endangered Species Act [ESA] and listing status of either threatened or endangered). While commonly assumed by the general public that fish ladders pass all fish species that are found in the waterways, fisheries biologists and engineers recognize that different fish species have significantly different swimming capacities (i.e., different sustained and burst speeds). Additionally, it is important to recognize that fish species also have different migratory drives and also use the water column differently at different period within their variable life history cycles.

As discussed earlier, fish ladders enable fish passage by breaking the total hydraulic head into manageable steps. But manageable by whom? Unfortunately, not every species. The head drop per pool, together with the fish ladder flow and the volume of each pool, directly affect the energy dissipation per pool. With all parameters equal, the greater the head drop, the greater the amount of energy to dissipate. For example, we know that the acceptable head drop per pool for salmon is 12-inches; however, the head drop for trout is only 6-inches [1]. Therefore, trout may not be able to ascend a ladder which was designed around some salmon species as the target fish. As biodiversity is understood to be a critical factor to a healthy ecosystem, there is renewed interest in making fish ladders more accessible to a greater variety of fish species. While greater accessibility is required, this need is clearly not yet the norm. A study has so far focused on target species and often times little is known about the swimming capabilities of non-target fish. The discussion and ultimate decision of "passable to which species" should take a primary focus at the onset of a project, as it will influence the selection of the most appropriate ladder type, head differential, and will also influence the overall cost of the project.

FP systems are efficient

Another common misconception is conventional fishways, no matter the type, are efficient at attracting and passing fish. There exist many types of conventional fishways which may be volitional or non-volitional. For the volitional types, there are chute types such as Denil and Alaska Steep pass, but also pool type such as pool and weir, weir and orifice, vertical slot, and hybrids such as pool and chute. For the non-volitional types, there are some mechanically complex solutions such as lift and lock and trap-and-haul facilities. Once again addressing assumptions common to the general public, fishways are often assumed to be volitional and provide a workable solution; however, not all volitional fishways are as efficient at attracting and passing fish. Figure 1 presents the attraction and passage efficiencies for ten different families of fish in four fishway types [2]; results of this study demonstrate that none of the fishway types evaluated were 100% effective at attracting and passing all fish from these ten common family groups. Fishway types should be selected based on site requirements, be context specific, and the designer should consider not just the hydraulics, but also the type of fish that will be utilizing the fishway. One specific example is with reference to a pool and weir design and the requirement to pass "bottom oriented fish." Acknowledging the plunging flow characteristics of this design and fish passage being restricted only at the water surface, fish species accustomed to the river bottom would be less likely to pass over a surface-oriented passage structure. Recent meta-analysis of fish passage literature [3]. Highlights differences in fish passage efficiency between different ecological guilds of fishes (pelagic or benthic; rheophilic or limnophilic) with study results suggesting that fishways were approximately 60% efficient on average in passing these differing fish guilds (again noting the current estimates by Herman Wanningen and that only approximately 30% of the fishways in the Netherlands work well).

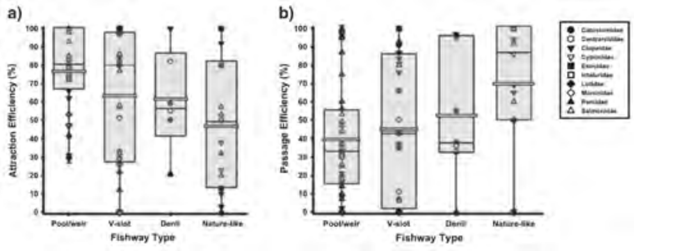

Figure 1: Fishway attraction and passage efficiency. Taken from Bunt, Castro-Santos, and Haro, Performance of Fish Passage Structures at Upstream Barriers to Migration, River research and applications [2].

Volitional passage is better

It is commonly assumed that volitional passage is better than non-volitional passage as the human interaction is removed, and nature does its thing. While there is some truth in this statement, volitional passage and its benefits may be misunderstood. When considering volitional passage and the associated hydraulic and engineering attributes to address, design elements such as vertical drop across the barrier as well as changes in water level and flow volume need to be critically evaluated. While not necessarily part of the hydraulic and engineering requirements, it is important to note certain field biological monitoring requirements that might be required when designing fish passage facilities. A few important topics that may need to be addressed tied specifically to volitional passage include the in advertent introductions of aquatic invasive species, un intended genetic impacts and/or hybridization of closely-related species, passage of certain fish species to upstream environments that are unsuitable for certain fish species (e.g., impaired water quality, unfavorable water temperature and dissolved oxygen conditions, etc.), unintended predation and/or expansion of certain predators (or prey) to delicate ecosystems, fish pathogen and fish health considerations, or migratory issues (migratory delays caused by excessive distance, thermal barriers, poor flow characteristics of large-reservoir environments, etc.).

While non-volitional fishways can present the same challenges noted above, they present a unique set of challenges and concerns as river connectivity is "broken" in the sense that direct migratory access is impeded, and fish cannot pass by their own will. Human interaction is required and can generally address this issue, yet the need for human interaction can also be highly controversial. Fish welfare is becoming a more common theme in fisheries management and concerns for how, when, and why fish are handled during the fish passage process receive greater scrutiny in modern design and planning discussions. While not always preferred from a fish welfare point of view, non-volitional fish passage does provide operators and fisheries managers with the opportunity to conduct research that is not always possible in truly volitional fish passage systems. Operators gain the ability to capture, mark, and tag fish species which enables estimates of passage efficiency, species diversity and passage capabilities, population estimates, brood stock collection, while also allowing the opportunity to remove or restrict non-native and/or invasive fish species to certain upstream environments. The obvious objective of fish passage is to provide passage in a timely, safely, and efficient manner.

Therefore, it is important for stakeholders to review the need to "intervene" by evaluating the need for sorting and monitoring.

While fisheries research objectives and practices are often valid and reasonable, they clearly impede the volitional and natural movement of migratory fish. Studies have their place to inform future decisions, but the initial goal to provide passage should not be lost to the human desire to control.

Sorting versus not sorting should be carefully evaluated as well as monitoring through active versus passive means.

Both volitional and non-volitional ladders have advantages and disadvantages. Before predetermining that one application is better than another, the stakeholders should clearly identify and evaluate the project goals and then determine the best fish passage application to achieve those goals.

All fish can jump

When people think of upstream migration and fish passing natural barriers, they may have the mental image of brown bears at the top of the Brooks Falls in Katmai National Park (Alaska) waiting for Sockeye Salmon *Oncorhynchus nerka* to jump directly into their mouths; a similar image of fish ascending a fish ladder by jumping from pool to pool could be envisioned Figure 2. However, when given the choice most fish would choose not to jump in order to minimize energy expenditure. Fish, like most living organisms, will generally choose the "path of least resistance" when given the choice. As defined by Wikipedia, the path of least resistance is "the physical or metaphorical pathway that provides the least resistance to forward motion by a given object or entity, among a set of alternative paths."

This concept is important to understand for fish passage systems because a well-designed fish ladder is one that provides safe, efficient, and effective fish passage.

The efficiency level is one that should result in the least energy expenditure in favor of energy conservation to access upstream migratory destinations.

It is thus a balance of water energy dissipation and fish energy conservation. Fish ladders such as pool and weir may be effective but come at energy cost which is not always the most efficient for all species and may reduce the capacity of a fish to reach its spawning grounds.

Figure 2: Typical fish ladder symbol.

Put it in and they will use it

This is a naïve approach to fish passage. Proper determination of a fish ladder type should consider: species complexity, fish behavior and swimming abilities, fish responses to hydraulic conditions including temperature variations, in addition to proper attraction flow, well designed entrances, and well-located exits. Importantly, "improper flow inside the fishway can negate any positive elements associated with the attraction flow and fishway entrance" [4]. In simplest terms, a well-designed fish ladder that is improperly located will prove to be of very little use.

Fish ladders are bi-directional

As a fish passage designer, the principal author has worked with stakeholders that have had the misconception that fish ladders can be used by fish to go up and down a barrier, the same way as a human may ascend or descend a ladder. Unfortunately for both fish and fish passage design engineers, this similarity in "ladder" use is not quite correct. In the case of the human, the person descending the ladder is likely the same person who just recently ascended it. Ladder use for fish is often associated with fish life stage; an anadromous fish ascending the ladder is likely a returning adult fish migrating upstream to spawn, while downstream anadromous migrants are often times juvenile fish on their way to the ocean. These different migratory life stages are critical as they are driven by different elements, such as olfactic cues freshets, water temperature, etc. In the case of downstream migration, fish are routinely known to migrate with an increase in water flow; in other words, the greater the flow imprint, the greater the likelihood of an increased number of fish migrating. In the case of downstream migrants, the fish ladder flow is only a very small proportion of the river flow (not considering the attraction flow) and if a fish ladder were required to pass fish downstream, juvenile fish would have a difficult time in locating the ladder given the minor flow associated with the ladder exit. For comparison purposes, Floating Surface Collectors (FSCs) are used to collect downstream migrants and are generally sized to have an attraction flow of approximately 2,000 cubic feet per second (cfs; 56.6 m^3/s) while a typical fish ladder may only have flows at or below 20 cfs (0.56 m^3/s). While the use of ladders for both fish and humans are easily confused, the use of an upstream passage fish ladder for downstream migration is ill advised as the poor collection efficiency of the fish ladder leads to overall poor passage performance.

WHAT ARE THE MOST COMMON REASONS FOR FAILURE?

There are three primary reasons why fishways do not always work as expected: inadequate or unclear goals, poor design, and inadequate operations and maintenance [5].

Unclear goals

Difficulty in development and application of project goals can come from multiple sources including possible hidden agendas from stakeholders, modification of goals during the project, lack of communication, not engaging the stakeholders at the right time, failing to establish goals at the onset of the project through a collaborative approach, as well as developing misunderstood, poorly-defined, or assumed goals. In developing project goals, it is paramount to engage the right people at the right time and importantly work through a collaborative and transparent approach, while documenting the discussions to develop achievable and measurable goals. In addition, while staff may change over the duration of the project, the project goals should not.

Once the goals are established, they become the road map for the design phase, construction, operation, maintenance, and monitoring. The important "next steps" once the facility is operational is to ensure that the constructed project meets the design criteria and that operational goals are followed. Common startup problems that may lead to an assumption that facilities are not operating as designed are often associated directly with incorrect operational protocols that vary from the base design criteria. Fish passage facilities are designed with specific design criteria developed that promote proper ladder operations (fish ladder will work within criteria and is safe, efficient, and effective within the design low and the design high flow conditions). Examples of operational protocols that can have a negative impact on fish passage efficiency include ladder operation outside of the design criteria, including operation at higher tail water elevations (some of lower pools may become submerged, velocities in the ladder may drop, and fish may not be motivated to use the ladder). Operation of the ladder in flow conditions that exceed the design flow (5% exceedance) may also negatively impact river conditions which may have a direct impact on fish behavior and migration (elevated flow conditions causing fish to temporarily cease upstream migration). In simplest terms, ladders might not be "operating" well because operators are not aware of the original design and operational goals of the facility. Fish ladders should not be expected to work as efficiently (or at all) outside of design criteria as if they are operated within criteria. Therefore, when evaluating the effectiveness of the completed project, the researcher must have a sound understanding of the agreed upon criteria for the project.

Finally, it may not be feasible to meet all criteria established for the project due to site specific circumstances. In this case, the stakeholders should investigate other avenues of providing passage, such as dam/barrier removal when feasible, accept reduced effectiveness, advance other adaptive management approach such as the use of hatchery or artificial spawning channels, or develop a habitat restoration program as a mitigation measure.

Poor design

This section explores the most common issues related to the design of a fish ladder.

Fishway entrance: The National Marine Fisheries Service (NMFS) notes the following with respect to fishway entrance design: "The most important aspects of a fishway entrance design are: 1) location of the entrance, 2) shape and amount of flow emanating from the entrance, 3) approach channel immediately downstream of the entrance, and 4) flexibility in operating the entrance flow to accommodate variations in tailrace elevation, stream flow conditions, and project operations" [1]. For the purposes of this paper, we will focus only on entrance location; while the additional three aspects above are critical; they are complex and could be the subject of their own paper.

Location is everything or nearly so and obviously, the ladder type and hydraulics within are critical for efficient fish passage, but just like real estate, entrance location is one of the prime essentials. If fish cannot find the fishway, the fishway becomes obsolete. The entrance shall be located at points where fish can easily locate the attraction flow and enter the fishway. When choosing an entrance location, high velocity and turbulent zones in a powerhouse or spillway tailrace should be avoided in favor of relatively tranquil zones adjacent to these areas. Again relying on NMFS guidelines, they note "at locations where the tailrace is wide, shallow, and turbulent, excavation to create a deeper, less turbulent holding zone adjacent to the fishway entrances may be required" [1]. Ideal entrance location is however not always feasible due to access, land ownership, adverse hydraulics etc. An important term to consider is "upstream terminus". The upstream terminus is the physical most upstream location that fish can ascend. In that area, fish would naturally agglomerate, and water should be tranquil during low flow conditions. The engineer would locate a fishway entrance at the upstream terminus but should also investigate the flow conditions during high flow events. It is possible that a normally-tranquil area during normal flows is not so during higher flows and that a hydraulic jump may form. Based on the linear separation between those two points between low and high flow, it may become necessary to add another entrance to the fishway to provide fish passage during all flow conditions.

When placing a fishway entrance at the upstream terminus is not feasible, it might be necessary to add a barrier to direct fish to a fishway entrance. Adding a barrier in the waterways to provide passage may sound counter-intuitive; however, fish should be able to readily find the entrance and not bypass it. A state-of-the-art fish ladder is useless if fish do not find it. Many different types of barriers exist, and the purpose of this paper is not to evaluate fish barrier type and pros and cons, but to remind the reader that prime location when not available can be created to achieve a similar outcome.

Attraction flow: Attraction flow emanating through the fishway entrance is crucial to attract fish to the entrance and weighs directly into the effectiveness determination of a fish ladder at passing fish. The fishway flow is generally not sufficient in itself to attract fish. The fishway flow is often combined with an auxiliary water supply (AWS) to make up the attraction flow. Per NMFS [1], "attraction flow from the fishway entrance should be between 5% and 10% of fish passage design high flow for streams with mean annual streamflows exceeding 1,000 cfs (28.3 m^3/s). For smaller streams, when feasible, use larger percentages (up to 100%) of streamflow. Generally speaking, the higher percentages of total river flow used for attraction into the fishway, the more effective the facility will be in providing upstream passage." In order to provide sufficient attraction flow, an AWS is generally added to address the need at the fishway entrance. Aspects to consider in the design of the AWS system include intake location, screening systems and how flows are diffused in the entrance and lower fishway pools, and importantly whether or not water supplying it is pumped or fed by gravity. In addition to the biological requirements, designers should also consider the operation and maintenance of the finished system. Some of the common pitfalls of an AWS system are insufficient flexibility and control, overly complex design that the operator does not understand how to optimize the operation, or using a water source different than the ambient water quality in the river. An important example in this regard is the tendency for fish to hold in the tailrace, creating a delay in migration, and not due to insufficient attraction flow, but because the water temperature is different than that in the river. This example is common in gravity systems with the AWS intake located at depth in the stratified forebay resulting in cooler attraction water versus the warmer water of the river hence creating a temperature barrier.

When feasible, the designer should use fisheries biological and behavioral information to utilize documented fish movement and natural flow patterns in the river, in order to increase attraction potential. In complex systems, a Computational Fluid Dynamic (CFD) model may be required to best understand the flow vectors and use additional flow (i.e., turbine flow) in symbiosis as more attraction flow is not always feasible (e.g., in the case of a pumped AWS system). In some cases, the use of a high velocity jet may be necessary to bring fish from the far field to the near field. However, this technology brings some complexity which is neither always desired nor needed and will be site- and project-specific in many cases.

Finally, while attraction flow is important, the designer should pay attention to false attraction in order to limit potential confusion from mixed flow pattern; false attraction in this case refers to non-entrance flows that come from one or more sources that serve to confuse fish with improper and unintended attraction flows (flows/sources not associated with the fish passage structure).

Poor hydraulics in the ladder: Each technical fish ladder has its own flow pattern and ways to dissipate energy. They each have non-uniform flow, with areas of faster moving water, areas with reversed flow direction, and thus areas that fish can utilize to pass or to rest during migration. While the goal of a fish ladder is to dissipate energy incrementally, allowing fish to ascend through a series of pool in which the energy is manageable, some ladders can be too turbulent to the target species and/or to other species utilizing the fish ladder. Turbulence has been shown to influence both swimming behavior and performance of fish [5-7]. The turbulence can be affected by fish ladder flow (too much flow), or by the hydraulic drop per pool (too much head), or by not enough volume (pool being too small). Varying any of these parameters could help reduce the turbulence. The energy dissipation factor is an important metric of turbulence. For example, the energy dissipation factor for salmon should be equal to or lower than 19.5 (m-kg/sec)/m^3(4.0 (ft-lbs/s)/ft^3) [1], however when designing for trout the energy dissipation factor should be reduced to 14.6 (m-kg/sec)/m^3(3.0 (ft-lbs/s)/ft^3 or lower. However, if the energy dissipation factor is too low, fish may not be motivated to ascend. The United States Fish and Wildlife Service (USFWS) [8] presents a species-specific energy dissipation factor criteria table; it is recommended to properly size the volume of the pool and appropriately select the hydraulic drop per pool to ensure the ladder will not be too turbulent, which would lead to a reduced efficiency.

The flow patterns in a fish ladder are directly related to the pool geometry. Larinier [9] recommends to not straying too far from the characteristics of existing fish ladders, which have proven to be effective over time. In addition, existing fishways might have orifice and weir coefficients based on regimented physical model research. Not only are they proven but are supported by data and monitoring effort. One may want to take freedoms with the geometry to try and best fit the site, but this should first be supported by physical or CFD modeling.

Improper exit locations: The fishway exit needs to be properly located so that when fish exit the ladder, they do not fall back through turbine intake, bypass, spillway, etc. Therefore, the exit should be located sufficiently upstream along a shoreline in a relatively tranquil zone where fish can exit safely and continue their upstream migration. There is no good rule of thumb for a minimum distance upstream of potential fall back area and the distance generally depends on bathymetry and associate river velocities. In addition to fall back when designing the fishway exit, USFWS [8] adds the following considerations: "The location of a fishway exit must consider: 1) possible exhaustion after swimming through a volitional fishway, 2) the risk for the fish to be overwhelmed by the surrounding flow field and either fall back downstream of the barrier or be entrained into the turbines; and 3) the potential for debris accumulation." It should be noted that other factors such as water temperature could contribute to fall back. For example, Sockeye Salmon successfully ascending the fish ladders on the Snake River but then exiting into warm water conditions upstream of the dam (associated with surface exit) and volitionally going back downstream through dam's spillway or turbines. The fishway exit is key here as exits need to receive extra design attention as they attenuate the effect of headwater fluctuations to create hydraulic conditions suitable for fish passage in the ladder. The hydraulic conditions should not be dissimilar to the fish ladder hydraulics as fish migration could be delayed, or fish could reject the exit pools and fall back within the ladder (see headwater variation next section). Poor hydraulic conditions can add significant stress and may result in exhaustion. Concerns associated with exhaustion come from possible predation from one or more sources (avian, small mammals, pinnipeds, etc.). Release location should consider ambient hydraulic conditions as well as possible escape from predator; in some cases, engineered log jams are used to provide refuge.

High variation in tail water and headwater elevation: Fish ladders can be designed to address some variation in the headwater and tail water elevation. Some ladder types, such as vertical slot, can self-regulate over a small variation band. Beyond that small variation, it is still possible to provide optimum hydraulic conditions supportive of successful fish passage; however the regulation system becomes increasingly mechanical, increasing cost, operation, and maintenance, and can possibly increase fish mortality and injury. In short, the design becomes more complex and the more complex it is, the less the operator will be able to run the ladder optimally and passage efficiency will decrease. Whenever possible, the design team and stakeholders should avoid high variations in water level over the design flow.

A high level in tailwater might mean that the ladder will need to have an adjustable weir gate or multiple gates, entrances at different elevations, or an adjustable slot opening. Additionally, low tailwater design needs to be evaluated during high flow events as increases in tailwater will mean that the low fish ladder pools would become submerged during high flow events and resulting in decreased pool velocities. One way to deal with decreased velocities in this type of event would to be adding AWS flow through floor or wall diffusers into the ladder to increase flow, and thus velocities. This addition may be required in order for fish to not hold during these periods and to encourage upstream movement.

To address variation in the headwater, the fish ladder needs to include flow control sections upstream of the facility designed for the highest headwater. There are several types of control sections including static (by means of a series of vertical slots or submerged orifices), mobile (by means of a series of adjustable sluices or regulating valves) or even more complex systems. Examples of the latter would include bypassing some pools, or by opening exits at various levels in the fish ladder [9]. Figure 3 provides examples of more complex designs. In the case of Schematic b (submerged orifices), this design works well hydraulically, however fish have been observed to sometimes reject the upper ladder section (i.e., flow control section) when the rest of the ladder is weir only. In the case of Schematic d (multiple exits), this relies heavily on proper operation often tied to system instrumentation and control (generally more complex).

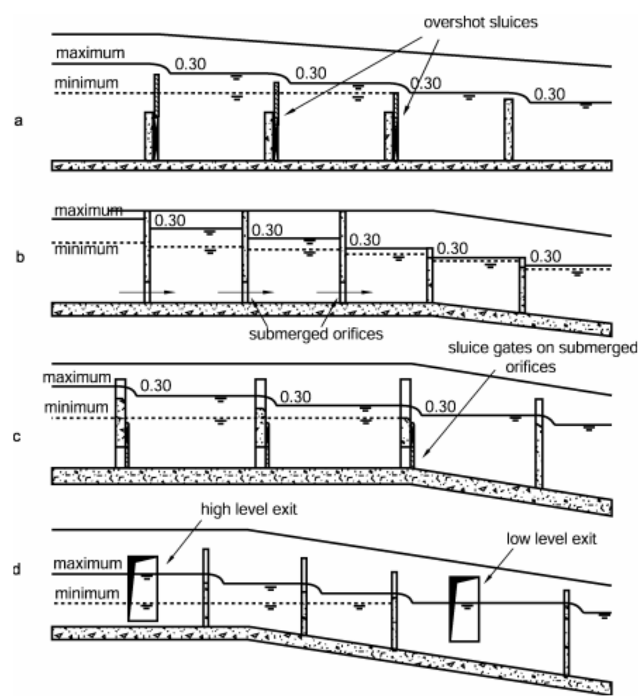

Figure 3: Schematic Plans Illustrating Flow Control Sections In Fishway [9]; Note, dimensions are in metric.

The principal author of this paper has experienced variations in tailwater of up to 18 feet (5.5 m) and in over 12 feet (3.7 m) in headwater variation. As a summary, the greater the variation, the more complex the system becomes and the designer must think beyond the hydraulics only; as there may be additional stressors to fish that could result in delay.

FP systems cannot be infinitely long, or can they:
Theoretically, fish ladders could be infinitely long if the turbulence is low, resting pools are provided, and the system is sized for a specific fish swimming ability. The energy expenditure will need to be evaluated to ensure safe, timely, and efficient fish passage. Some of the longest fish runs are attributed to Sockeye Salmon traveling more than 900 miles (1,500 Kilometers) and climbing more than 6,500 feet (1,980 m) in elevation from the Pacific Ocean to their natal waters in the Sawtooth Valley of Idaho (NMFS, 2015) [10]. Highlighting the endurance of some fish species, the height of a fish ladder is generally governed by the height of the barrier/dam that fish should pass upstream of. Some of the highest dams in the Pacific Northwest of the United States where fish passage is provided through technical fish ladders are on the mainstem of the Columbia River and on the Snake River (a tributary of the Columbia) where fish ladders range in height from 70 to 105 feet. The tallest fish ladder known by the author is the Portland General Electric's (PGE) North Fork facility, a two-mile long fish ladder providing passage over the Faraday Diversion Dam (100 feet [30.5 m]) and the North Fork dam (120 feet [36.6 m]), for a total of 220 feet (67.1 m) in vertical rise. Europe's longest ladder pales in comparison; the Geesthacht ladder located on the Elbe River in northern Germany is 0.34 miles (550 m) long and has approximately 45 pools. Clearly, fish ladders in the Pacific Northwest are some of the largest in the world.

When the vertical rise is important, a rule of thumb is to add a resting pool at every ten pools, or double the size of the pools, such as at the Ice Harbor Dam, Bonneville Dam, or Geesthacht barrier. If the forebay water elevation fluctuates heavily and the reservoir is potentially confusing for fish to navigate, or there is known water quality issue in the reservoir, the designer may consider other fish passage alternatives, such as trap-and-haul facility, lock, or brail systems. Mechanical facilities are typically selected when volitional passage would be less successful, or when it has a lower life cycle costs compared to volitional passage.

Inadequate operations and maintenance

Emphasis on operations and maintenance, or lack of, is often associated with fish ladder effectiveness. As noted by the U.S. Office of Technology Assessment, "Without proper maintenance, even perfectly designed fishways can be rendered useless" [4]; fish ladders can be incorrectly labeled as ineffective or poorly designed when a lack of routine in operations and maintenance and system upkeep is commonly the root cause of the system performance. Inherent with the proper design and operation of the system, it is extremely important to design a simple and intuitive project with proper access for the operations and maintenance crew to do their work without going into some unreasonable length, preparation and training. The more technical the ladder with the more controls for the AWS system, entrance conditions, or fish ladder exits, the more difficult it will be to operate the facility optimally. There may be a need to include instrumentation and controls as part of the design to simplify the processes and support the operator. The designers should not only do a constructability review of the facility but also an operation and maintenance review of the facility, going through each step/procedure to ensure the full design is addressed (i.e., proper access, size and weight of system components as well as installation/removal, anchors points for items such as davit cranes, ease of the facility dewatering, availability of spare parts, etc.). One of the goals during this review is to eliminate or reduce risk through design and simplify operations and maintenance to the extent possible.

WHAT ELSE IS IMPORTANT?

Geotechnical

Fish ladders are located along waterways, often providing passage at man-made barriers. These barriers, such as dams for hydropower, are often built in deep canyons with competent rock to ensure stability of the dam. This in itself means that access to build the fish ladder may be complex and may govern the final layout of the ladder, as well as the cofferdam and dewatering methods required during construction. In addition, the layout is often constrained by the topography and thus fish ladders are often built on the face or abutment of a concrete dam, on bedrock, or in fluvial and alluvial material.

For the case of bedrock, while the final facility will likely meet any requirements related to stability analysis, the rock excavation will likely be expensive and will require a specialty firm to perform the excavation, through either drilling and blasting, wedging, sledging, barring, breaking up with power-operated tools, and/or controlled fracturing dependent on the rock hardness. In the case of drilling and blasting, a vibration monitoring plan will be required to establish appropriate maximum limit for peak particle velocity for each structure or facility that is adjacent to or near the work. Establishing a vibration limit is important to preclude permanent settlement of soil or architectural or structural damage to nearby structures.

For the case of fluvial and alluvial material, which are saturated soil deposits that have been created by sedimentations in rivers and lakes, the designer needs to consider liquefaction potential? The sedimentation processes sort particles into uniform grain sizes and deposit them in loose state which tend to densify when shaken by earthquakes. The tendency for densification leads to increasing pore water pressure and decreasing strength [11]. It is important to perform geotechnical investigation to better understand the stratification, soil composition, and compaction of the material. If it is identified that liquefiable materials exist at the site, these can be removed and replaced, vibro and dynamically compacted, grout can be injected, or pile foundation extending down to competent soil or bedrock can be added. These mitigation methods can add considerable cost.

Changing conditions

Changing conditions may be environmental, such as different water quality, water temperature, or flow rates. These changes may be the result of climate change. Change in conditions may be stakeholder imposed, with changes to target species and the need to increase efficiency to a greater range of species, increasing the operation window, and/or increasing the low and high tailwater elevations. However, addressing changes in conditions may be very difficult with a concrete structure which offers very little flexibility. It is therefore difficult to adapt and modify the fish ladder to accommodate the variations.

The flexibility for adaptive management should be built into the design, which means that the facility needs to be built with the unexpected in mind. How to size the facility for adaptive management while staying within budget and not oversize the facility? There is often a fine line when planning for changing conditions, which can be categorized as a risk. Risk is often counterbalanced by money. How much shall one invest to reduce a potential risk? This equation is often left to the owner to decide. Engineers can assist owners with one or more recommendations to aid in adaptive management. The first rule would be to not design to a value (e.g., a specific ladder flow), but perform a sensitivity analysis to understand the possible variations and limitations; the second is to design the hydraulics with factor of safety not dissimilar than those used in structural design; the third is to evaluate the facility during design to understand its limitation and, if possible, built in some operation cushion.

COST "RULE OF THUMB"

Technical fish ladder construction costs vary greatly based on fish ladder type, flow requirement, site geology, access, variation in tailwater and headwater, and also the need for cofferdam and dewatering methods during construction. In order to prepare an engineer's estimate for an American Association of Cost Engineering (AACE) Class 5 Concept Screening based on judgment and analogy, a "rule of thumb" may be appropriate. A class 5 estimate has a low range of -20% to -50% and a high range of +30% and +100%. Katopodis [12] documented in his Introduction to Fishway Design that unit costs in Washington and Oregon ranged from $10,000 Canadian Dollars (CAD) per meter rise for small weir fishways to CAD $200,000 per meter rise for a vertical slot fishway with flow control, multiple entrances, AWS and flood and debris protection. This equates to approximately US $56,000 per foot of rise in 2021 dollars for the vertical slot. The primary author has used an estimate of US $110,000 per pool in 2021 dollars per prior work experience from a noted fish passage expert [13]. This rule of thumb is interesting, because it does not tie the actual costs to vertical rise but to the number of pools. For example, if the vertical drop per pool is 6-inches instead of 1-foot, it does not divide the cost of the pool by two.

These rule of thumb guidelines do not include project management, design development and management, construction management costs, or escalation rate to mid-point of construction, overhead, profit, construction bond, insurance, taxes etc. The project cost could easily double based on actual future construction date, material pricing variation due to unforeseen conditions (e.g., pandemic), and current economic and political environments. These rules of thumb shall be validated with design refinement, quantity take off, current material cost, quotes, and construction approach, but can generally be used for concept screening or alternative evaluation studies.

DISCUSSION

This paper reviews some of the misconceptions of upstream fish passage through technical fish ladders, as well as the most common failures contributing to reduce efficiency level, such as unclear goals, poor design, and inadequate operation and maintenance. This paper also reviews additional important items such as geotechnical considerations and changing conditions. It also concludes with some rules of thumb for cost estimating.

While engineers may be inclined to use a "plug and play" approach to fishway design or simply employ rigid design criteria standards established by regulatory agencies, it is important to understand that each location and design is unique and that key design elements addressed within this document should be understood and validated for the range of fish species that utilize the ladder. Ideally, it is important to review the fish ladder design from three point of views: 1) the fish view approaching, entering, ascending, and exiting the ladder, 2) the contractor view on how the facility will be built starting from access, coffer-dam, dewatering, etc., and 3) finally from the operator and maintenance crew to ensure staff safety, proper access to equipment, and ensure a simple intuitive system easy to operate with fail safe options.

CONCLUSION

In addressing recent global trends, the designer needs to think about changing conditions (e.g., global warming) and the growing need to design ladders ever more passable to greater number of fish species in order to support biodiversity. Finally, dam and barrier removal, while seen by many as the best fish passage solution, is not the only solution; future populations will continue to have a need for multiple renewable power sources as well as some degree of water storage and as a result, will continue to need further development of the second-best solution (i.e., fish ladders) and rendering them more efficient for a wide range of fish species and diverse operational considerations.

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