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Adaptive fishway design: a framework and rationale for effective evaluations

Theodore Castro-Santos

Introduction

Scientific understanding of the effects of dams on fish and other aquatic organisms has been advancing rapidly in recent years (AGOSTINHO et al. 2005; MORITA & YAMAMOTO 2002; WAPLES et al. 2008). Humans have been building dams for millenia, and the first attempts to mitigate these effects date back centuries. It is only recently, however, that tools have become available to help us understand the extent to which dams and other anthropogenic barriers restrict movements, and the effects of these barriers on populations and ecosystems. This paper reviews developments in techniques of fishway evaluations and offers some suggestions for standardized evaluation methods that can direct modifications and improvements to future designs.

During the 20th century several factors arose that led to advances in fishway development and evaluations. The development of efficient hydro-turbines at the end of the 19th century created an incentive to build ever-larger and taller dams. This led to a dramatic increase in construction of large dams during the first half of the 20th century. Soon after, laws and treaties providing protection for migratory fish species were put into effect. This created a mandate to develop more effective fishways. At the same time, advances in hydraulic engineering made it possible to dissipate the head associated with high dams in ways that were shown to improve passability. Hydraulic engineers working in Europe and North America made important advances to fishway designs during this period (British Institution of Civil Engineers 1942; DENIL 1909, 1937; MCLEOD & NEMENYI 1940).

Biological understanding of the requirements of fishway design lagged behind these engineering advances. Early studies of fishway performance were largely restricted to determining whether individuals of a given species could pass a short section of fishway (MCLEOD & NEMENYI 1940), and to largely qualitative descriptions of swimming and leaping performance (DOW 1962; STRINGHAM 1924). Laboratory methods were eventually developed for quantifying swimming performance that provided the first theoretical rationale for fishway design (BRETT 1962, 1964, 1967). By this time, however, many fundamentals of fishway design had already been established, with some empirical (mostly laboratory-based) performance data to support them (COLLINS 1962; COLLINS & ELLING 1960; GAULEY & THOMPSON 1962; ORSBORN 1987). To a large extent, the effect of these developments in biology was to establish or confirm existing design thresholds. These thresholds largely consisted of criteria meant to ensure that flow velocities within fishways were below what a limited number of target fish species were able to traverse.

Quantifying performance

Since the mid-20th century, advances in monitoring technologies and movement theory have provided a more nuanced view of the need for and purpose of fishways. Most recently fishways have come to be employed as a tool in the greater effort to restore ecological connectivity in riverine systems that have become highly fragmented and otherwise altered (BLOCH 1999). To do this, fishways are expected to pass a range of taxa, including many species of vertebrates, as well as some invertebrates. Regardless of taxon, however, the goal of fish passage is the same: to expedite passage for native species.

In order to expedite passage, three processes have to be optimized, each occurring in a different location relative to the fishway: Fish must first find the fishway entrance (‘Approach zone’, for upstream passage this might be the tailrace of a dam); then they must enter the fishway (‘Entry zone’, an area near the fishway entrance where the entrance can be detected using hydraulic and other cues); finally, they must ascend (or descend) and exit the fishway (‘Passage zone’, within the fishway itself; Figure 1). The processes are sequential, and each can be completely quantified as time-dependent rates:

$$\Pr(Advancing) \times dt^{-1} \qquad (1)$$

Where Pr(*Advancing*) is proportion of the available population moving into the next process in the sequence, and *dt* refers to a change in unit time. For each process, a countervening rate occurs as fish abandon the Entry zone, fishway, etc:

$$\Pr(Retreating) \times dt^{-1} \qquad (2)$$

Where Pr(*Retreating*) is the proportion reversing direction or otherwise departing a given zone. Here, each proportion refers to movement from one zone to the next. As such, the units of Equations 1 and 2 can be thought of as representing distance time^{-1}, the appropriate units for movement rate.

This differs from a strict measurement of velocity, however, because the distance units refer to transition between zones (Approach, Entry, etc.). The scale at which distance and time are important will vary depending on context (open river movements vs. fishway passage vs. turbine passage). Also, these two rates should be thought of as competing with each other for a mutually exclusive outcome – a fish that advances is no longer available to retreat, and one that retreats can no longer advance. Each individual has the potential to realize either fate so long as they are present within a particular zone. This is referred to as a ‘competing risks’ scenario in the survival analysis literature, and has important implications for quantification of movement patterns (ALLISON 1995; CASTRO-SANTOS & HARO 2003; CASTRO-SANTOS & PERRY 2012; See ‘Data Analysis Methods’ below).

When evaluating passage within a fishway, it may be more useful to characterize passage explicitly in terms of distance:

$$\Pr(Passing) \times dD^{-1} \qquad (3)$$

Where *dD* is the distance traversed or height ascended.

It is important to understand, though, that the physiological and behavioral processes that lead to forward or backward movement are time-dependent, and distance of ascent is the result of rates of forward movement (Equation 1) and failure (Equation 2). Ultimately the goal of fishways is to maximize the first rate while minimizing the second. We must understand the roles of each of these rates if we hope to improve passage.

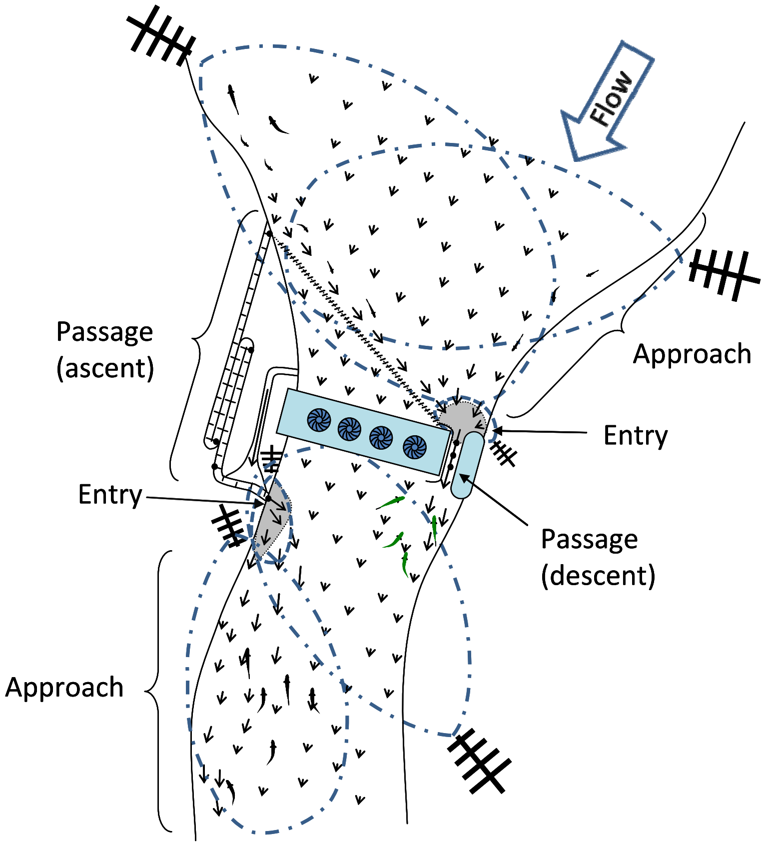

Figure 1: Schematic of typical upstream and downstream fishways at a hydro plant. Zones of Approach, Entry, and Passage are marked. Entry zones are depicted as shaded areas at fishway entrances. Thin arrows indicate flow vectors (length corresponds to velocity). Note attraction flow provided for upstream guidance to left of powerhouse and angled bar racks for downstream guidance upstream of the powerhouse. Antenna arrays are also depicted showing how radio telemetry can be used to identify when individual fish enter and exit each zone (aerials are represented in bold black, ovoids are detection zones with dash-dot monitoring Approach zones and short dashes monitoring Entry zones). Black dots depict PIT antennas deployed for monitoring upstream and downstream Entry and Passage.

Common practices for evaluating fishways

Evidence of passage

In the 19th century (and in many cases even today) managers viewed fishways as successful if they saw evidence of spawning upstream of the structure (PRINCE 1914; ROGERS 1892). The assumption was that if even a few individuals can pass a structure, then the structure must be passable to all individuals of that population. Evidence for this mindset can be seen today in fish passage design manuals, where specifications are provided for species and size classes, with little if any consideration of individual variability in swimming performance or migratory motivation (BELL 1991; LARINIER 2002).

Managers should not be criticized too harshly for this perspective: often the only evaluation tool available to them was surveys of upstream habitat – they had no way to monitor movements of fish through the structures. Moreover, the objective for building these structures was to provide access to habitat, and if there was evidence that that was occurring then it was not unreasonable to consider that structure a success.

Counts

Probably the most common method for evaluating fishways today is to count numbers of fish passing a structure. Various methods can be used to provide visual counts: many fishways are equipped with monitoring windows staffed with live counters. Video is also often used, and recent advances in image processing technology allow counters to view only those clips where fish are present. Hydroacoustics (SONAR and DIDSON) can also be effective for enumerating targets, sometimes even allowing automated species assignment (ENZENHOFER et al. 1998). Hydroacoustic techniques are of greatest value for downstream passage, where deep, quiescent forebay environments make it possible to monitor movements and quantify passage routes (SKALSKI et al. 1996; STEIG & JOHNSTON 1996). The shallow depth and highly air-entrained environments of many fishways, however, largely precludes the use of hydroacoustics in the vicinity of these structures (THORNE 1998; TREVORROW 1998).The use of visual counts and their acoustic analogues holds an intuitive appeal – the better a fishway performs the more fish it should pass. There is an important logical flaw in this thinking, however: the number of individuals passing a structure is a function of both the number trying to pass and the passage rate. In order for fish counts to be an adequate measure of fishway performance the following criteria must be met: 1) the number attempting to pass must be known; 2) arrival timing for the population passing must be known; 3) individuals can only be counted once – fallback must be negligible. A corollary of criterion 3 is that movement must either be unidirectional, or the observer must be able to account for both upstream and downstream movements of individuals. Without the aid of tagging technology these three criteria cannot be met except perhaps for very small, closed populations.

Where sequential fishways exist on river systems it may be possible to satisfy the first 2 criteria for all but the first fishway. Without being able to identify individuals, however, the third criterion cannot be met. This may be acceptable if each fishway in a sequence rapidly passes the entire population of available fish. Such fishways might be deemed fully successful with no further monitoring required. Examples of this are rare, however, even among salmonid populations for which fishways are broadly thought to be effective. Also, the performance of the first fishway in the sequence cannot be known: even if estimates of populations below the dam are available (e. g. as might be provided with hydroacoustics), the duration of exposures and identity of individuals is typically not estimable. At best, video and acoustic monitoring should be thought of as a screening test: if the criteria can be met and passage meets management goals then video can be a sufficient evaluation tool. If either the criteria or management goals are not met, however, other methods must be employed to evaluate passage.

In addition to evaluating performance, fishway counts are also often used as population indices of migratory fish. This may be the greatest value of fishway counts, and many long-term datasets are available that document runs, especially of anadromous fish species. Although widely used, these indices should also be viewed with caution because they only indicate how many fish passed the structure, not how many were available to pass. If passage performance were constant across years, then this would be a reliable index. Performance can vary widely, however, with environmental conditions (temperature, discharge), hydroelectric facility operations, and physiological state of migrants (SULLIVAN 2004; ZABEL et al. 2008). Thus fishway counts are of greatest value for long-term monitoring and trends, but in order to understand annual variability in performance more reliable methods are required.

Mark-Recapture

Mark-recapture techniques are one of the best-established ways to estimate population size, and can be a very effective tool for measuring passage performance. Techniques of mark-recapture include visual marks (e. g. external marking or tagging), biological marks (e. g., genetic identifiers, otolith marking, etc), and telemetry. Visual and biological marks can be useful, especially for batch marking large numbers of individuals. However they typically require that individuals be physically re-captured and handled, which can affect their behavior. More importantly, although successful fish can be easily captured in fishways, this may require obstructing passage of large numbers of untagged individuals. Finally, these methods do not provide ready estimates of how many tagged fish even approach the fishway. Telemetry, in contrast, allows monitors to detect fish as they approach and pass each structure, and so offers a far more appropriate set of tools for fishway evaluations. The following subsection describes the three most common forms of telemetry and describes their application to fishway performance monitoring and evaluation.

Radio and Acoustic telemetry

The past two decades have seen dramatic advances in the field of wildlife telemetry, with many of the advances being developed specifically to address questions of fish passage. Both radio and acoustic telemetry allow users to tag individual fish and monitor their movements over a range of scales. Tags can be coded to transmit unique identifiers; some systems are able to discriminate among several hundreds of codes on a single frequency. A particularly useful feature of radio telemetry is that radio antennas and receivers can be tuned to manage detection range. This allows users to quickly and effectively identify movements among Approach, Entry, and Passage zones (Figure 1). A recent book documents details of the development of this technology and offers many specifics on application (ADAMS et al. 2012).

Radio telemetry tags fall into two broad categories: active and PIT (for passive integrated transponders). Active tags carry a battery and can be programmed to transmit their codes at user-specified rates. Signals from these tags can be detected over very large distances (even by orbiting satellites in some cases); range is correlated with power consumption, though, and to maximize battery life most transmitters have a maximum working range of < 1 km through air. One concern common to all telemetry methods is that when multiple tags are present within a detection range it is possible for signals to collide, causing missed reads. This can be avoided with tags and receivers that operate on more than one frequency. Some receivers are able to simultaneously monitor all frequencies within a fairly broad band (e. g. 1 MHz). Most receivers have to scan among frequencies, however, which means that detection efficiency decreases with increasing frequency number.

PIT tags do not carry batteries; instead they are built with induction coils that are charged when the tag passes near or through an antenna. These tags are typically small (1 x 8 mm - 3 x 32 mm) and hermetically sealed in glass or plastic capsules, which offers the advantage of nearly unlimited functional life. PIT detectors operate at very high rates (tens of reads per second). The tags only function over short ranges however: in most cases tags must be < 1 m of an antenna to be detected. Antennas themselves can be larger, however, and can be easily constructed to span slots and weirs of dimensions common to fishways; in some cases they can even span small rivers (FRANKLIN et al. 2012). This makes them ideal for documenting entry into and passage through fishways (CASTRO-SANTOS et al. 1996; SULLIVAN et al. 2001; FRANKLIN et al. 2012; Figure 1). Moreover, their short detection range precludes detection outside the fishway, where signals from active tags can often penetrate through solid structures providing a false impression of entry. Also, the rapid read rate means that PIT detectors can monitor brief passage events, such as sprinting through a slot or downstream passage at a sluiceway. Active tags fire slowly, and have larger but typically less precise read range. While this makes them less effective for monitoring brief passage events, they are more effective at monitoring longer events, like Approach and Entry. Thus these two forms of radio telemetry complement each other and make an excellent combination for evaluating fish passage.

One limitation of PIT and active radio telemetry is that both types are sensitive to radio-frequency (RF) noise and interference. Interfering signals can be conducted along power cables and can be transmitted through air. With increasing use of radio bandwidths for communications this issue promises to become an increasing problem. Those planning monitoring programs and experiments will do well to first survey the bandwidths in their study area. Tags can then be built that transmit on those bands with the least amount of noise for that location.

A second important limitation for radio telemetry is that transmissions are rapidly attenuated in water. This problem is most severe in saltwater, where attenuation is almost complete even in very shallow depths. Attenuation is not a problem in riverine applications where fish swim within a few meters of the surface. Where fish swim near the bottom of deep rivers or lakes, radio may still be useful over short distances (10's of meters), especially if receiving antennas can be placed below the water surface. This technique can also help eliminate problems of transmitted RF noise. Where long detection distances are required for fish moving at depth, however, radio telemetry may not be an effective tool for monitoring movements.

Acoustic telemetry can work well in those very environments where radio is ineffective. Similar to radio, acoustic tags can transmit unique codes. Some systems are able to detect signals over multiple frequencies. Under optimal conditions, acoustic tags can be detected over a range of 100's of meters – appropriate distances for broad-scale monitoring of movements. Some manufacturers have developed methods for triangulating position of tags based on the different arrival times of signals to hydrophones arranged in carefully designed arrays. In some cases the position of the tag can be resolved to within a few centimeters. This ability helps to counter a significant weakness of acoustic systems: sensitivity and detection range can vary widely at a given location depending on water chemistry, turbidity, and presence of acoustic noise (e. g. from wind, currents, boat traffic, etc.). In the absence of multiple redundant receivers that can triangulate position or similar methods, precision of these instruments can be poor, limiting the value of the data they provide.

Where fine-scale positioning is possible, significant time investments are typically necessary to ensure that only reliable transmissions are used. The data this method provides can be used to characterize approach, and even entry into fishways, although these metrics really do not require the level of resolution that can be achieved, and most of the information provided by acoustic triangulation falls outside the scope of quantifying passage performance. Also, acoustic telemetry does not work in confined spaces with high amounts of entrained air, such as is found within fishways. These issues limit the value of acoustic telemetry technology for monitoring fish passage.

Perhaps the greatest promise of acoustic telemetry (and the same can be said for fine-scale radio applications) lies in the ability to couple detailed movement data with information on hydrodynamics and how complex flow patterns influence orientation and navigation. Fish possess highly specialized mechanosensory structures that allow some species to detect small fluctuations in flow. How fish respond to these fluctuations and how this relates to other sensory and environmental stimuli (e. g. vision, smell, etc.) remains poorly understood and represents one of the greatest research needs in understanding how to best to locate and design fishways relative to dams, powerhouses, and riverbed morphology. Predictive models developed coupling computational fluid dynamics models (CFD) with acoustic and other forms of telemetry and hydroacoustics suggests that this may provide a very powerful tool for improving both upstream and downstream passage (GOODWIN et al. 2006; NESTLER et al. 2008).

Data analysis methods

The fact that fish may either advance or retreat from a given zone (Equations 1 and 2) complicates analysis of telemetry data. When presence in a given zone can terminate in more than one way the researcher must calculate rates based on those individuals that are present and available to advance or retreat, regardless of which event terminates that presence. Once the individual leaves the zone, however, it must no longer contribute to rate calculations. A set of statistical tools developed for clinical trials, actuarial applications, and materials testing (collectively called ‘survival analysis’) is well-suited to accommodate this feature (see CASTRO-SANTOS 2004, 2011; CASTRO-SANTOS & HARO 2003; and ZABEL et al. 2008 for details on these techniques and their application to fish passage). These tools allow researchers to measure competing rates of advance and retreat, while eliminating the bias caused by the fact that both rates are acting on individuals simultaneously. Importantly, these methods allow for calculation of effects of covariates (velocity, turbulence, temperature) on those rates, thereby allowing managers and researchers to identify specific conditions that act to limit or enhance passage.

Where detailed movement studies are available, they indicate that existing and widespread standards of fishway design are far from optimal for passage of a range of species, and that much more work is needed if we hope to provide passage for the multitude of aquatic organisms that use rivers as movement corridors.

Case studies

Recent work has called into question the effectiveness of fish passage and other river restoration techniques. Perhaps more troubling is the fact that post-construction monitoring and evaluation are the rare exception, rather than the rule. This is true of river restoration programs generally (BERNHARDT et al. 2005), and also for fishways in particular. A recent meta-analysis combed the peer-reviewed and gray literature to determine whether certain fishway types are more effective than others (BUNT et al. 2011). The authors identified more than 100 published studies purporting to evaluate fishways, but only 19 of these provided enough information to determine what proportion of fish entered and passed the respective fishways. Among those fishways that had received this minimal level of evaluation performance ranged widely, both within and among fishway types and species groups. The variability in performance was so great that the authors concluded that no compelling evidence yet exists to support any one fishway design; worse, those designs in common use cannot be expected to reliably pass any species (Figure 2).

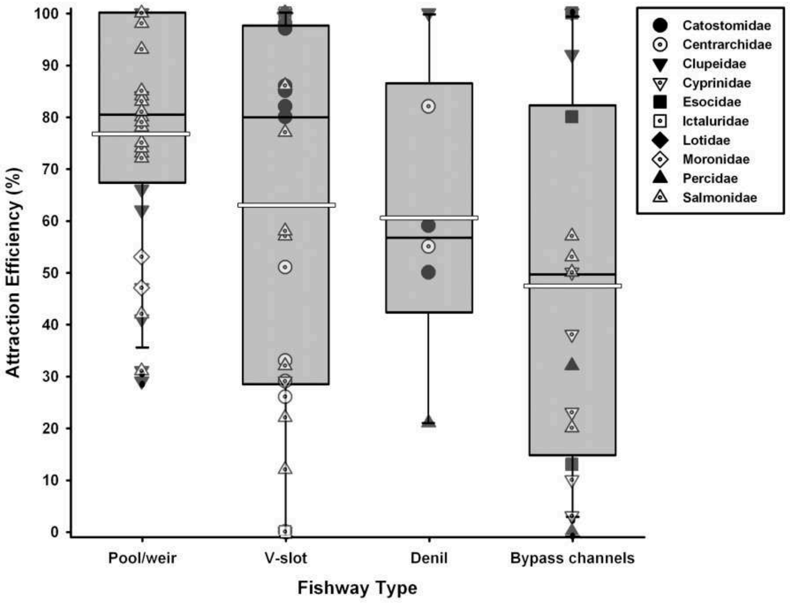

Figure 2a: Percent attraction (approach x entry) by fishway type.
Reprinted with permission from BUNT et al. (2011)

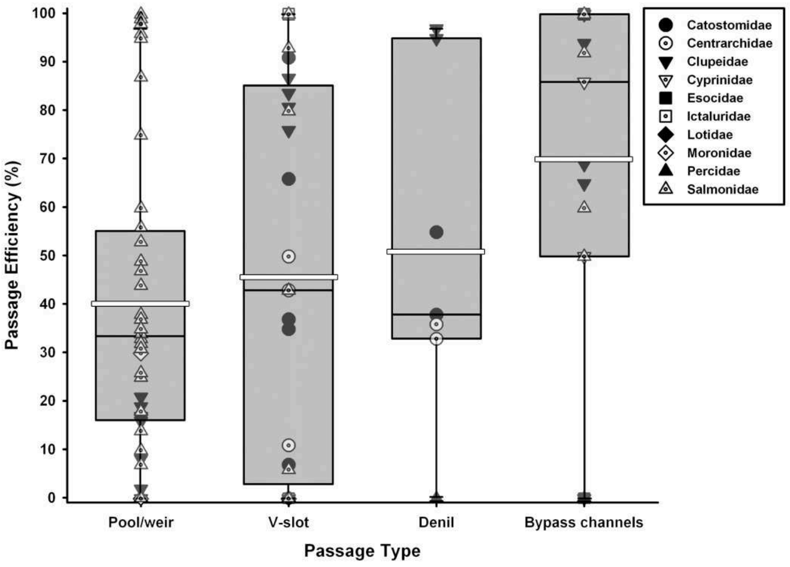

Figure 2b: Percent passage by fishway type. Note the broad variability in performance both here and in Figure 2a.
Redrawn with permission from BUNT et al. (2011).

The work by BUNT et al. (2011) required that fishway evaluations separate out passage for fish that enter fishways from the proportion entering. As stated above, however, there are two steps that must occur before fish even enter the fishway: they must first approach and locate the fishway entrance, and then they must actually enter the structure (Figure 1).

Work that colleagues and I have performed at fishways on the Connecticut River has illustrated the importance of including all three steps in evaluations (CASTRO-SANTOS & HARO 2010; CASTRO-SANTOS & LETCHER 2010; SULLIVAN et al. 2001). The Turners Falls dam and fishway complex (Connecticut River, USA, RKm 194) creates a serious barrier to passage of American shad (*Alosa sapidissima*). Because they have passed tens of thousands of American shad in some years, these fishways have been widely hailed as models of effective shad passage (LARINIER & TRAVADE 2002; MOFFITT et al. 1982; RIDEOUT et al. 1985). Those claims of effectiveness were entirely based on numbers of individuals passing, however. As dicussed earlier, this approach overlooks the important question of how many fish are actually entering the fishway. We began our evaluations of passage at Turners Falls using PIT telemetry in 1999, later we coupled PIT and active radio telemetry, and that work continues today. In the case of Cabot Ladder – the first fishway in the system, and once thought to be a highly effective fishway – passage proportions range from 3 - 17 %. This failure was manifest in the distance that fish are able to ascend the ladder (Figures 3 and 4). The mechanism of the failure, though, can be better understood by considering the competing rates of success and failure: shad abandon the ladder at greater rate than they ascend (Figure 5), which produces a consistently low passage rate.

Figure 3: Cabot fishway, RKm 194 on the Connecticut River, Massachusetts USA. Constructed in 1980**,** this fishway has probably never passed shad effectively.

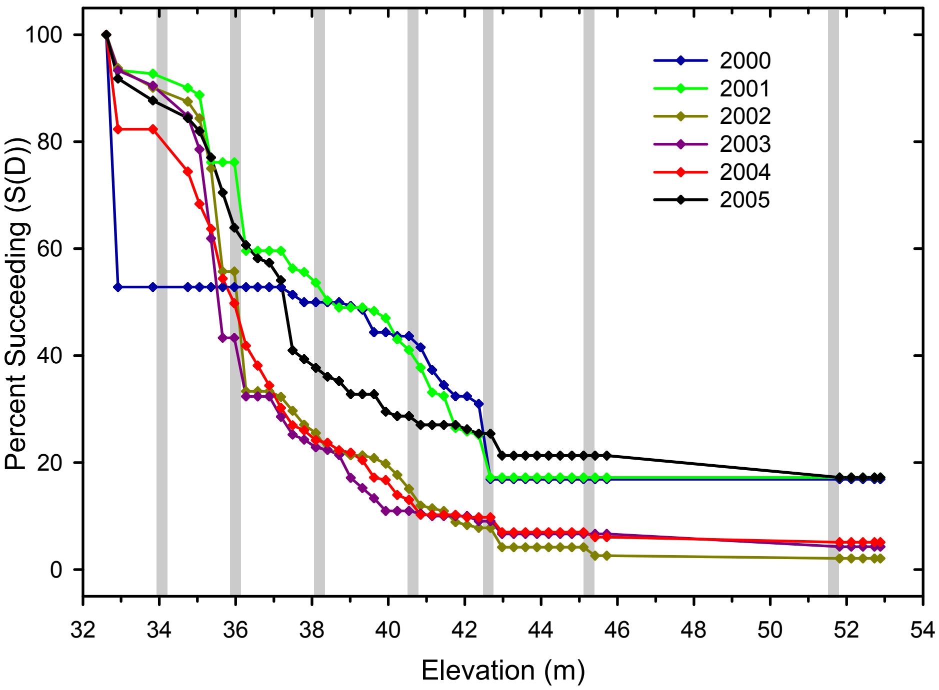

Figure 4: Results of 6 years of PIT telemetry at Cabot Ladder (Figure 3). Gray bars indicate turnpools, dots indicate individual PIT antenna locations and percent arriving to each antenna.

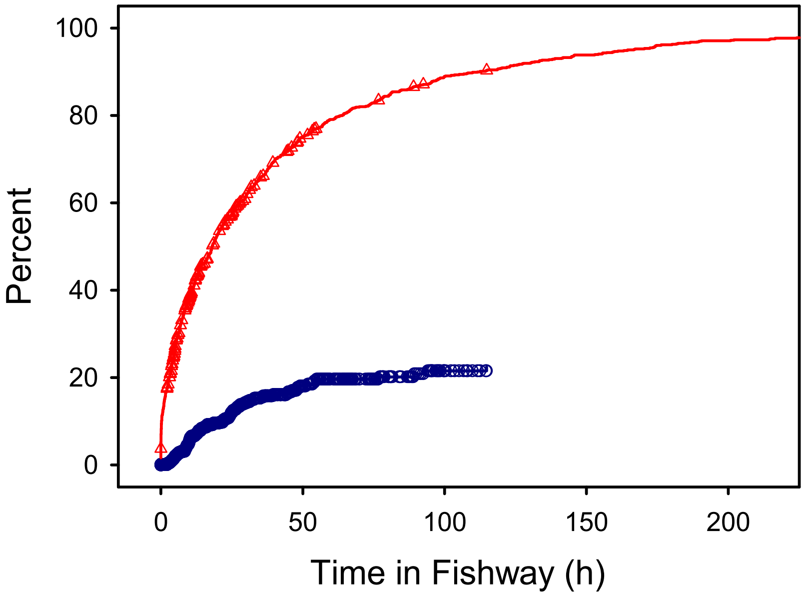

Figure 5: Time to pass (blue) vs. time to fail (red) of American shad in the Cabot fishway. Lines are modified Kaplan-Meier curves (KAPLAN & MEIER 1958) and are least-biased estimates of cumulative distribution functions that would be expected if only one endpoint were available. Circles and triangles represent censored observations, i. e. for the passage curve they represent residence times for individuals that did not pass and for the failure curve they represent passage times of successful passers. Note that failure rate always much greater than passage rate – this is the cause of the poor passage success shown in Figure 2a.

Despite multiple changes to this fishway improvements have been marginal, and plans are underway to replace it with a fishlift. This is an important lesson of the importance of performing evaluations as part of fishway design: the fishway was completed in 1980 at a cost of about $10 million and operated for almost 20 years before its poor performance was documented in a way that managers could act on. Now it must be replaced at even greater cost. Mounting evidence suggests that poor performance at this and other fishways in the system have contributed to declines in the very populations they were intended to enhance (CASTRO-SANTOS & LETCHER 2010).

Although passage through Cabot Ladder is poor, approach and entry appear to be satisfactory (about half of the shad passed at the next dam downstream enter the fishway (SULLIVAN 2004)). Other fishways in the complex have the opposite problem, however. At the uppermost fishway in the system (Gatehouse Ladder) shad pass at in comparatively high proportions (about 60 % of shad that enter successfully pass). However fewer than half the shad that attempt to pass Gatehouse Ladder ever encounter the original fishway entrance (low approach rate), and those that do often fail to enter (low entry rate). A series of modifications begun in 2007 has yielded a greater than 4-fold improvement in passage rate at Gatehouse Ladder, and work is ongoing to improve this further. Thus at the Turners Falls we have examples of failure in each of the three steps: Approach, Entry, and Passage. Successful resolution of these problems is now being realized, but only because we were able to differentiate among the sources of failure.

Conclusions

Fishways are expected to restore ecological connectivity to fragmented riverine systems by expediting passage for a range of taxa. Several factors will determine the effectiveness of these structures. These factors include biomechanics (locomotion) and physiology (endurance, motivation), as well as behavior (orientation, optimization; swimming, climbing, etc.). Limitations to any one of these factors can preclude successful fishway performance, and there is a pressing need to advance our understanding of all three factors with respect to fish passage.

Expeditious passage requires that fish be able to pass a structure with a minimum of delay, stress, injury, or exposure to direct or indirect anthropogenic influences. In short, it means that fishways should eliminate the impediments to movement caused by dams and impoundments. Ultimately, any organism for which passage is provided must complete the three steps of fishway passage: Approach, Entry, and Passage. Biologists and engineers must collaborate to understand how well fishways are performing, and what solutions are likely to improve passage where problems occur. Available evidence has shown that existing designs cannot be expected to reliably expedite passage. Even so-called nature-like fishways have largely failed to deliver on their promise to expedite passage for a broad range of taxa (BUNT et al. 2011). Given that passage provisions remain a priority worldwide, it is all the more important that managers and engineers adopt an adaptive management approach to the design and construction of fishways. With widespread application of evaluations that measure performance standards with clear biological relevance it may become possible to better understand the relationship between design and performance – a relationship that at the moment continues to elude us.

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