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Review

Improving the reliability of fishway attraction and passage efficiency estimates to inform fishway engineering, science, and practice

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ABSTRACT

Of late there have been several syntheses that consider the biological effectiveness of fishways. These syntheses emphasize the importance of generating estimates of attraction and passage efficiency, using electronic tagging techniques, as the "gold standard" for determining if a fishway is indeed successful at passing target species upstream to meet ecological, management, and conservation goals. Such an emphasis on efficiency is potentially problematic if estimates of attraction and passage efficiency are biased or otherwise fail to reliably represent the true biological effectiveness of a fishway. Indeed, erroneous estimates could lead to management decisions (in terms of both design criteria and operational decisions) that are costly in terms of economic expenditures and failed conservation outcomes for populations, species and ecosystems. Here we review the factors that are necessary to consider when determining the reliability of efficiency estimates for fishways and provide suggestions for improving such estimates. Clearly there is need for greater attention to the effects of various capture (including gear and the timing and location of capture), handling, and tagging protocols on fish necessary to monitor individual passage success given the potential for procedures to influence organismal condition and behavior. In addition, there is need for more long-term tagging studies (monitoring individuals across multiple seasons), mechanistic studies to understand the biological basis for differences in efficiency estimates, greater use of control studies to account for natural levels of migration failure/behavioral heterogeneity, technical validation of electronic tagging equipment (to account for tag failure and detection efficiency), and the use of approaches that combine individual monitoring with population-level studies (including modeling exercises). Also relevant is the need to better understand the proportion of fish that need to pass a fishway to address ecological, management and conservation targets, as well as identify the proportion of a population that is actually motivated to attempt passage in a given season. Failure to think critically about the factors for a given study/site that have the potential to influence estimates of passage and attraction efficiency will impede the ability of science and monitoring activities to inform fishway design and operation and ultimately improve aquatic ecosystems.

1. Context and objectives

Widespread human development activities associated with hydropower, irrigation, flood control, and drinking water that involve placement of barriers on lotic systems have had negative consequences on riverine ecosystems (Dynesius and Nilsson, 1994; Poff et al., 1997; Malmqvist and Rundle, 2002). One of the most obvious negative consequences is the alteration of longitudinal connectivity, particularly in the context of fish migrations (Jungwirth et al., 1998; Nilsson et al., 2005; Cooke et al., 2012a,b). Depending on the type and height of barriers, environmental conditions (e.g., water temperature, turbidity), organismal morphology (e.g., shape, body size, fin position), and the physiological and behavioral capacity of migrants, some barriers are simply impassable to upstream migrating fish seeking areas to feed or reproduce (Larinier, 2001; Katopodis and Aadland, 2006). Even if barriers are passable, there can be migration delays and not all fish (both individuals and species) may be successful (reviewed in Novak et al., 2003; Roscoe and Hinch, 2010; Noonan et al., 2012). In the context of ecological engineering (Mitsch et al., 2002; Mitsch, 2012), engineers working collaboratively with fish biologists have designed a variety of structures to facilitate upstream movement of fish past

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barriers, often referred to as fish passage facilities, fish ladders, or fishways (Clay, 1995; herein called fishways). For the purpose of this paper we consider fishways to include the full suite of structures including mechanical facilities such as elevators/lifts and locks that use active means to pass fish upstream, as well as constructed fishways (e.g. Denil, pool and orifice, vertical slot and nature-like) that passively rely on a fishes ability to ascend (see Clay, 1995 and Odeh, 1999 for examples). Although most fishways are intended to facilitate bi-directional movement (Calles and Greenberg, 2009), rarely do they function in that manner. Here we focus on upstream passage but suggest that many of the issues discussed are also relevant to downstream fish passage. In general, knowledge of downstream fish passage is lacking (Larinier and Travade, 2002; Pavlov et al., 2002) except perhaps for salmon smolts (e.g., Bickford and Skalski, 2000; Scruton et al., 2007). Obviously understanding both upstream and downstream passage is critical given that there is no point in facilitating upstream passage if downstream passage either is not available or kills a large proportion of the fish (adults, larvae, eggs or juveniles; McLaughlin et al., 2012).

The first attempts to design fishways were based on the premise of "build it and they will use it". However, by the mid 1900s greater emphasis on the application of engineering and scientific principles to fishway design became more common. Early efforts focused on laboratory hydraulic studies or "paper" exercises where simple biological design criteria (e.g., maximum sustained swimming speeds for a target species) were used to determine if a given engineering design would match the swimming capabilities of fish (summarized in Katopodis, 1992, 2005; Rodriguez et al., 2006; Katopodis and Williams, 2012). However, despite using sophisticated modeling approaches to derive fishway passage predictions based on time to fatigue data (Neary, 2012), failed passage still occurs and disentangling the mechanisms for this failed passage can typically only be conducted through field studies. In the few instances where post-construction monitoring was conducted (96 published examples according to Roscoe and Hinch, 2010), a fishway would typically be deemed to be effective if target species were observed to ascend the fishway (e.g., captured in trap, visual observations). More recently (i.e., 1990s; e.g., Odeh, 1999), there was a recognition that evaluating the number of fish found to ascend a fishway failed to account for those that either failed to find the entrance to the fishway or that entered but failed to successfully ascend the fishway (Katopodis and Williams, 2012). To that end, the notion of fishway attraction and passage efficiency was embraced, coincident with the expansion of electronic tagging technology in freshwater systems (Lucas and Baras, 2000; Cooke et al., 2013) and its application to fishway studies (Reviewed in Cooke and Thorstad, 2012; Bunt et al., 2012) which enabled the generation of efficiency estimates.

Here we adopt definitions of attraction and passage efficiency used by Bunt et al. (2012) where attraction efficiency was defined as the proportion of fish tagged and released during a given study that are subsequently located within less than approximately 3m from a fishway entrance (Bunt et al., 1999) or at the base of a barrier to fish movement and near enough to a fishway entrance for fish to detect fishway attraction flow (Aarestrup et al., 2003). Entrance efficiency is the proportion of tagged fish attracted to the facility that actually enter the structure. Further, passage efficiency is commonly calculated by dividing the number of fish of a particular species that exit a fishway by the number that are detected at the fishway entrance (Bunt et al., 1999; Aarestrup et al., 2003). Total efficiency is regarded as the proportion of all fish tagged that exit the fishway but in some studies it is calculated as attraction efficiency % times passage efficiency %. Fishway efficiency measures are regarded as the "gold standard" for evaluating the biological effectiveness of existing fishways and informing the design of new ones (see below for full suite of management uses for such estimates). When a value is reported, it is usually taken at face-value as being reliable and representative of the wider population. However, if attraction efficiency is determined to be low, is it actually so? And if passage efficiency is high, is that really the case? The consequences associated with using biased, unreliable and/or erroneous estimates of efficiency are potentially economically and ecologically costly. Here we provide a brief overview of how efficiency estimates are generated, consider the ramifications of unreliable estimates of fishway efficiency, consider the factors that can influence the passage and attraction efficiency and the reliability of efficiency estimates, and identify strategies for improving the reliability of passage efficiency. The purpose of this paper is to stimulate scientists to think about how the reliability of fishway efficiency estimates can be improved and practitioners (especially managers, regulators and engineers) to think critically about the reliability of the values used to support decision making.

2. How are efficiency estimates generated?

We wish to preface this section by noting that qualitative assessment of the ability of a fishway to pass target species is often called 'effectiveness' (Larinier, 2001) compared to quantitative estimates of passage efficiency. In our world view, effectiveness is a higher order process in which estimates of efficiency are a component. For example, effectiveness should be based around the ability of a fishway to achieve management and ecological objectives rather than only meeting some arbitrary target of passage efficiency. In other words, biological effectiveness of fishways requires a variety of information of which efficiency estimates are an important component, but certainly not the only component (see Pompeu et al., 2012).

For reliable estimates of attraction and passage efficiency, fish must be marked or tagged in some manner and that they are then recaptured, tracked or otherwise observed (e.g., underwater video) either at or near the entrance of the fishway and at the exit of the fishway. Mark recapture studies can introduce a number of challenges including difficulty of recapturing fish at the entrance such that when mark recapture approaches are used, they tend to only be for fish that reach the top and tend to preclude the ability to tease out the attraction and passage efficiency components (Schmetterling et al., 2002). And video studies, which benefit from not having to handle fish, are subject to bias in terms of not being able to easily identify individual fish (e.g., can lead to double counting; Hard and Kynard, 1997) and cannot be used to estimate attraction efficiency. For that reason, electronic tags have become the preferred (and really only) approach for generating estimates of attraction and passage efficiency. Use of passive integrated transponders (Castro-Santos et al., 1996), radio transmitters (e.g., Bunt et al., 1999; Moser et al., 2002), and on occasion acoustic telemetry transmitters (Roscoe et al., 2011), provide scientists with the ability to tag and release animals downstream of the fishway and then monitor their behavior and success as they attempt to locate the entrance and then ascend a fishway. Indeed, in their meta-analysis, Bunt et al. (2012) only included estimates generated using those three telemetric techniques. Fish can be tracked manually or fixed receiving stations can be installed that monitor the presence/absence of fish no matter when they interact with the fishway (see Cooke et al., 2013 for details on typical telemetry equipment for doing such studies). At a minimum there needs to be the ability to monitor fish in and around the entrance and at the top of the fishway to generate the information needed to calculate attraction and passage efficiency (as per the definitions presented above from Bunt et al., 2012). However, many studies include more detailed information on passage behavior within the fishway (e.g., time spent in different locations; see Gowans et al., 1999; Bunt et al., 2000; energetics of passage; see Hinch and Bratty, 2000; Scruton et al., 2007) based on extensive manual tracking, placement of antennas or hydrophones throughout the fishway, and in some cases use of physiological sensors (e.g., electromyograms, acceleration; Cooke et al., 2004).

An inherent component of all electronic tagging-based efficiency studies is the need to capture fish to affix or implant a tag. For fish raised in hatchery environments and tagged prior to release, this can be done in a controlled setting. However, for most fishway assessments, wild fish need to be collected using different passive (e.g., fyke nets, short-set gill nets) and active (e.g., angling, dip nets, seine nets, electrofishing) collection gears. Some studies also capture fish for tagging from a trap at the top of the fishway (Thiem et al., in press) or dip net them from within pools or turning basins (Roscoe et al., 2010). Once captured, fish need to be kept alive and in good condition prior to tagging and release. Methods for affixing or implanting electronic tags are reasonably well developed (summarized in Bridger et al., 2001; Cooke et al., 2011) and often first require use of sedatives to immobilize the fish (Ross and Ross, 1999). After the tagging procedure, fish are released (at some location – may be site of capture or other location) and the tracking can begin.

When manual tracking, fish are generally positioned frequently (usually radio tracking) and their migration paths recorded with GPS or on scale maps (Pon et al., 2009). If tracking does not occur at night (or on weekends) passage events could be missed. In addition, it is difficult to track multiple individuals simultaneously which is problematic if actual attraction or passage events happen quickly. Positioning error is a reality of manual tracking (Cooke et al., 2013) and safety concerns may limit the proximity of the tracker to the transmitter. Automated fixed telemetry requires placement of antennas or hydrophones at various locations in and around the fishway. Depending on the technology, environmental conditions, and characteristics of the fishway, it may not be possible to monitor positions in all locations. Fixed stations must be tuned and monitored (including use of test tags) to ensure that they are functioning properly and have high levels of detection efficiency. Use of paired antennas is needed to determine directionality (e.g., a single antenna at the top of the fishway could yield a detection but the individual may turn around and descend the fishway rather than exiting) of movement (and thus success). Some studies have combined manual and fixed tracking which can be effective for continuous monitoring of key locations (e.g., fishway entrance and exit) while simultaneously doing focal monitoring of individual fish (e.g., Pon et al., 2009).

3. Potential factors that influence fishway efficiency estimates

In an ideal sense, 100% of the variation in attraction and passage efficiency would be explained by biological characteristics of the fish (e.g., morphology, behavior, physiological capacity, motivation), environmental conditions, and characteristics of fishway design and operation. Moreover, the relationships and components of variation would be well understood. When Bunt et al. (2012) used principal components analysis and logistic regression modeling they revealed that variation in fish attraction was driven by biological characteristics of the fish that were studied (first four components of the PCA cumulatively explained 100% of variation), whereas variation in fish passage was related to fishway type, slope and elevation change (cumulatively explained 89% of variation). Nonetheless, there is still an underlying assumption that the values for efficiency themselves are not influenced by other factors that would lead to systematic or random variation and contribute to spurious relationships among biological, environmental and fishway characteristics. So what aside from these factors could influence the estimates? Here we summarize a variety of factors related to how estimates are generated that have the potential to influence estimates.

3.1. Capture method

Capture of fish requires use of a variety of gear types, all of which result in some level of stress and injury (even if minimal; see Table 1). There is a reasonable amount of research on the effects of electrofishing on fish (Snyder, 2003). Data on fish condition from net capture or rod and reel comes from work on bycatch (Davis and Olla, 2000) and catch-and-release recreational fishing (Cooke and Suski, 2005; Cooke and Sneddon, 2007), respectively. Although researchers can learn from these various studies to understand the potential biological consequences of capture on fish, and to identify strategies for minimizing stress and injury, there is still reasonably little known about the behavioral consequences of different capture-related stressors which is highly relevant for efficiency estimates. It is also worth noting that a stressed state and reproductive state are generally incompatible (Schreck et al., 2001) which is relevant given that most periods of intense fishway use (and nearly all fishway evaluations) are tied to reproductive periods (Roscoe and Hinch, 2010). If fish were to be injured (e.g., fin fraying, scale loss) and/or exhibit physiological disturbances (e.g., exhaustion of tissue energy stores, accumulation of metabolites, elevated metabolic rates) from capture, there is also the potential for behavioral consequences (see Schreck et al., 1997) that could alter both attraction and passage efficiency. For example, attraction is mediated by a close coupling of sensory physiology and behavior such that if there were injuries or physiological impairments that decoupled that relationship, attraction estimates could be low. Stress from capture can result in both hyperactivity and hypoactivity post-release (reviewed in Arlinghaus et al., 2007) which could both inflate or deflate efficiency estimates. Above some threshold (e.g., in lactate; Jain and Farrell, 2003), physiological disturbance would impede capacity to ascend the fishway. However, at this point such thresholds are poorly understood. Also relevant is that severe injury and stress can lead to mortality (e.g., post-release predation) or fall-back from the system (which would lead to under-estimates of attraction).

3.2. Capture location

The location of capture is relevant for studies of fishway efficiency. Capture of fish downstream from a fishway assumes that they are all indeed motivated to migrate and have a need to do so which may not be the case if the capture techniques also targets individuals that are not reproductively active or that are making use of spawning habitat downstream of the barrier. Sometimes fish are sourced by dip-netting within fishways (Roscoe et al., 2011) or collection from a trap at the top (e.g., Bunt et al., 1999; Thiem et al., 2011), tagged and then released downstream with the assumption that they will be representative of naïve migrants. The extent to which previous history with successful migration (i.e., fish captured from the trap at the top of the fishway) enables fish to learn how to find and successfully ascend a fishway is unknown, which could inflate estimates of efficiency. Likewise, if fish that already have ascended a fishway are tagged, it is conceivable that they have exhausted their energetic resources, have experienced metabolic acidosis, or accumulated an oxygen debt such that they

Table 1
Overview of capture methods typically used to obtain fish for generating fishway efficiency estimates and their associated issues (strengths and weaknesses).

Capture technique	Issues
Electrofishing	-Stuns fish which can lead to disorientation -Some species are sensitive to electricity -Rapid recovery (minutes) for most species with minimal injury
Passive pot gear	-Difficult to use in large lotic systems -Can result in injury or stress while fish are entrapped or during the period that fish are removed from net
Tangle gear	-Often results in injury and exhaustion as fish struggle to escape -One of the few gears that tends to work (often as drift nets) immediately downstream of fishways
Seine nets	-Difficult to use in large lotic systems and often ineffective for large fish species -Minimal stress or injury
Angling	-Some level of stress and injury inevitable -Heavy gear can be used to land fish rapidly -Most effective for gamefish
Drum line	-Some level of stress and injury inevitable -Lines need to be checked regularly to minimize physiological exhaustion
Dip net	-Typically most effective in or near fishways -Minimally stressful if done properly -Technique commonly used for adult Pacific salmon
Fishway trap	-If trap is at top of fishway the fish collected will have previous (and recent) experience with passage -Densities in traps can be high -Fish must be removed from trap (either by dip netting or by removing trap from water) -Does not require boat or other capture gear
Culture or hatchery facility	-Fish need to be transported from captivity to release site (stress) -Fish may not be of wild origin or indicative of the behavior or motivation of fish in the system -Fish may not be used to environmental conditions at release site

are unable to attempt ascent again. Bunt et al. (2012) excluded fish that ascended the fishway and were release downstream from their meta-analysis for these reasons. Also relevant is where (in a lateral sense) capture occurs relative to the barrier, fishway entrance, and attraction flows. For example, collection of fish from only one river bank could alter estimates if those individuals are biased toward swimming on that bank. Similarly, if fish are captured at the entrance to a fishway it is possible that they have already attempted passage several times and failed and thus may be physiologically compromised. Sourcing fish from well downstream of a fishway (will depend on biology of species) is likely to result in tagging of individuals which have not recently encountered the fishway. However, it is also worth considering whether fish captured downstream may lack the motivation or need to ascend the fishway.

3.3. *Release location*

The location of release is also relevant for estimates of fishway efficiency, independent of how fish were captured. For example, if fish are captured downstream, they can be released at site of capture. They could also be released at fixed sites (e.g., perhaps on both river banks and at various locations downstream in an experimental context or at a single site). Sometimes fish are released in the attraction flow, at the fishway entrance, or even in different locations within a fishway to identify specific locations of areas that are problematic for passage. Although useful for identifying specific issues, any estimates of efficiency generated using those approaches introduce biases. As such, release locations must be carefully considered.

3.4. *Timing*

The timing of capture, tagging and release (which is intimately linked to capture methods and locations) has the potential to influence efficiency estimates. For example, if tagging were to occur during the peak of migration when fish had accumulated below a barrier, capture and tagging could result in fallback downstream of the fishway (e.g., Frank et al., 2009) which would impede the ability to characterize migration behavior and evaluate passage efficiency. Moreover, if there were delays associated with physiological alterations and recovery (from capture or tagging) fish may be forced to migrate outside of the optimal migration timing window which could reduce their motivation to migrate or expose them to environmental conditions that are challenging (e.g., higher or lower flows or temperatures). If fish are held for a period of time (even short periods) for tagging or experimental purposes, it is also possible for that time in captivity to induce stress and potentially alter passage ability (Portz et al., 2006).

3.5. *Tagging method and anesthesia*

The type of tagging method has the potential to influence efficiency estimates. For example, any tagging approach that reduces the swimming performance (e.g., through physiological impairment from procedure or the burden of the tag, including drag if external) of a tagged fish has the potential to deflate estimates of efficiency. Most studies of swimming performance post-tagging reveal some level of impairment in the short-term (reviewed in Cooke et al., 2011), but with long-term impairments typically only present when tag burdens are high (actual burden varies among species and life-stage). Intra-coelomic implantation (or injection of PIT tags) is regarded as the best approach for long-term studies given that retention is high (Cooke et al., 2011), but if the expectation is that animals will want/need to ascend a fishway within hours to days post-release, then use of protocols that enable rapid attachment (e.g., gastric, external, PIT injection) are ideal. Tag loss (e.g., gastric expulsion or external tag shedding), however, could lead to underestimates of fishway efficiency. Animal care protocols require that anesthesia be used for most invasive procedures, including attachment and implantation (Borski and Hodson, 2003). Sometimes external tagging, injection of PIT tags, and gastric tagging can be done without anesthesia, but that may accentuate the stress of handling and tagging. Anesthesia is necessary for intra-coelomic surgical implantation to immobilize the fish for surgery and also to address welfare concerns. However, anesthesia is itself a physiological challenge from which fish must recover (Ross and Ross, 1999) presumably before they have the capacity to locate, enter and ascend a fishway. In addition, for fish that home using olfaction (e.g., Pacific salmon), some anesthetics such as clove oil have been suspected of impeding olfactory ability. At this point there is no empirical support for such concern (Yamamoto et al., 2008) but nonetheless such possibilities should be considered.

3.6. Equipment performance and reliability

Not surprisingly, various technologies have different strengths and weaknesses. have different strengths and weaknesses. For efficiency studies, an important consideration is the reliability of tags and tracking systems. For example, if tags fail (or their battery expires), there is the potential to underestimate efficiency when such fish actually ascend the fishway but are not detected. Similarly, if the manual tracking protocols do not follow fish continuously (e.g., only track during daylight hours) or if there are technical limitations with fixed monitoring systems, underestimates of efficiency are likely. In PIT systems, there may be problems with detection efficiency as well as inability to read multiple tags if tagged fish are swimming near antennas in close proximity (Castro-Santos et al., 1996). Some radio telemetry systems require sequential scanning of multiple antennas and/or multiple frequencies such that not all antennas and fish are monitored simultaneously (e.g., Bunt et al., 2000). And with both acoustic and radio telemetry, there can also be problems with signal collisions which can preclude detecting important events or even generate false detections (which could lead to an over-estimate of efficiency). Equipment failure can also occur as a result of power outages and variable environmental conditions can influence equipment performance.

3.7. Fallback after passage

In the Pacific northwest of North America, a number of studies have documented fallback whereby fish successfully ascend a fishway but then fall back over/through a dam rather than continue on their upstream journey (e.g., Boggs et al., 2004). It is important to note, however, that fallback may be a natural phenomenon associated with searching behavior of fish (i.e., not all migrations are entirely unidirectional). Nonetheless, fallback (no matter the reason) can cause a number of problems including injury or death and behavioral impairments (e.g., migration delays). In addition, given that fishway counts in the Columbia Basin serve as the primary method for estimating escapement of Pacific salmon, fallback can induce significant bias (e.g., if a fish presumed to have passed actually falls back). The issue is greater for counts (e.g., using video) than for tagging studied (Naughton et al., 2006), but nonetheless, if care is not taken to understand and quantify fallback it has the potential to be misleading when interpreting data from efficiency studies.

4. Ramifications of getting efficiency estimates wrong

Recently there have been calls for more monitoring of fishways post-construction with a focus on evaluating efficiency (DFO, 2007; Roscoe and Hinch, 2010; National Marine Fisheries Service, 2011). Such information would be used to determine which designs are best suited for a given system and species and in some cases can be used to refine existing design or operations. To demonstrate the variability in the range of efficiency estimates that have been generated, consider a recent meta-analysis by Bunt et al. (2012). For example, attraction efficiency for pool-and-weir fishways range from 29 to 100%, vertical-slot from 0 to 100%, Denil from 21 to 100%, and nature-like from 0 to 100%. Similarly, passage efficiency was also highly variable; nature-like fishways, 0–100%, Denil, 0–97%, vertical-slot, 0–100%, and pool-and-weir, 0–100%. Mean and median values differed among device types leading the authors to conclude that they could not clearly justify recommendations for any particular fishway type. Nonetheless, nature-like fishways tended to have the highest passage efficiency while pool-and-weir fishways had the highest attraction efficiency (Bunt et al., 2012). Indeed, there was an inverse relationship between mean passage efficiency and mean attraction efficiency by fishway structure type (Bunt et al., 2012). Because of the emphasis put on efficiency estimates by the scientific community (usually fisheries scientists), it is easy to see why and how environmental managers and regulators would use such information to guide decision making (including which type of devices to select for new facilities). However, doing so implies that the efficiency estimates generated are indeed reflective of the wider population/community as are the trends regarding which fishway types are optimal for a given scenario (e.g., including the meta-analysis described above). Obviously if that is not the case, the socio-economic and ecological costs could be severe. At the end of the day, attraction and passage efficiency are both relevant but it is overall efficiency that is perhaps most important. A fishway that had low attraction efficiency yet high passage efficiency for a given species may pass as many fish as one with high attraction efficiency yet low passage efficiency. Without context in terms of the population dynamics, life history, and habitat characteristics both downstream and upstream of a barrier, efficiency estimates of any type are difficult to evaluate in terms of the information value for management.

Overestimation of attraction efficiency could lead to the erroneous conclusion that fish are able to adequately locate and enter a given device (and associated configuration and flows) which could result in operational decisions (e.g., selection of flows) that are not optimal for fish, the public good, or the operator. Overestimation of passage efficiency would suggest that the device itself is functional and that conservation and management targets could be achieved. Clearly, any decision making regarding the operation or modification for a given fishway would be wrong, not to mention that such information could be exported and used for decision making elsewhere. If expensive fishway designs that do not have good efficiency are promoted, then there is a direct economic cost. Of course, there are even greater costs to fish populations and the entire aquatic (and even terrestrial) ecosystem if insufficient fish are passing such that the ecosystem services that fish provide (e.g., delivery of nutrients, recreational opportunities) are not fully realized which would lead to a variety of additional indirect ecological and socio-economic costs (Holmlund and Hammer, 1999). In developing countries where freshwater fish provide important sources of protein and nutrients, over-estimates in passage efficiency could even affect livelihoods and food security (Smith et al., 2005). In addition, passage estimates could be used in various decision support tools and models such that other potential restoration, enhancement and management strategies may be foregone if there is the incorrect belief (i.e., model input) that passage targets are being met (e.g., modeling the effect of passage efficiency on populations). Our purpose here is not to specify what those targets should be but we do note that Lucas and Baras (2000) suggest that 90 to 100% efficiency should be the target. Failure to engage in other restoration of stock enhancement strategies if one erroneously concluded that efficiency was "high" would be particularly problematic for species with life-history characteristics such as being long-lived and low reproductive output such that any population-level impacts would not be readily apparent in the short term. Barriers that are actually detrimental to an at-risk species could be deemed to not be a threat and thus not the focus of threat assessments and recovery planning. In a worst case scenario context, a species could be extirpated from a system if decisions based on erroneous over-estimates of fishway efficiency are utilized. When legal or other regulatory requirements (e.g., measuring regulatory compliance) are linked to passage efficiency estimates (e.g., Schilt, 2007), an overestimation could result in lost penalties being collected by governments on behalf of the public trust.

Underestimation of attraction and passage efficiency could also have a number of undesirable consequences. For example, increasingly there is the recognition that barriers can impede the spread of invasive species (e.g., sea lamprey) such that selective fish passage is desirable (McLaughlin et al., 2007). If attraction and passage efficiency are deemed to be low, when actually they are high, then decisions regarding invasive species control would likely not be optimal. In addition, if efficiency was deemed to be so low that structural or operational changes were needed, extensive economic costs may be incurred, while potentially seeing no benefit to efficiency. This could also play out on an inter-specific or even intra-specific (e.g., size, sex) basis whereby underestimates for one group could lead to management actions that result in real reductions in efficiency for another group. In addition, those designing and selecting from various fishway types and configurations may avoid a certain type of design (or design characteristic) if there is evidence that attraction and/or passage efficiency are poor for a target species. In some cases (especially salmonids), density-dependent processes on spawning grounds are such that it is desirable to limit escapement. Erroneous passage of higher numbers of animals than needed could lead to density-dependent mortality. It is also worth noting that in some jurisdictions there are legal ramifications associated with passage of fish such that erroneous underestimation could lead to unfounded legal or regulatory actions (with substantial economic costs) such that there is a strong justification to get the estimates "right" (Brown et al., 2011).

Particularly problematic is if the reliability of estimates vary among species or life-stages (e.g., by size, age or sex) or by fishway type. For example, if small fish are burdened by tagging such that their estimates are deflated, while larger fish are not, there could be future management actions that could negatively affect estimates for a wide range of species and multiple ages and life-stages. Similarly, if telemetry infrastructure is more reliable in nature-like fishways (e.g., due to lack of concrete and metal construction materials and interference with signals and reception) than in other designs, one could erroneously conclude that nature-like fishways have higher passage efficiency.

5. Assessing the reliability of efficiency estimates

We are not suggesting that existing estimates of efficiency are not useful. Instead, we suggest that each study must be carefully examined to identify the factors (beyond those relating to the biology, environmental conditions and fishway characteristics) that could have contributed to a given estimate. For example, using studies on which one or both of us are authors or have assisted in the research, we can objectively identify some issues that must be considered when evaluating the reliability of efficiency estimates. Thiem et al. (2011) used an experimental approach where lake sturgeon were captured in tangle nets downstream from a fishway, tagged (with PIT tags), and released into the entrance of a vertical slot fishway with a fence structure installed such that the tagged fish were unable to exit out the downstream end of the fishway. The experiment was repeated five times over different environmental conditions. Passage efficiency was estimated to be 36% across the five studies; it was obviously not possible to calculate attraction efficiency. However, does that mean that 64% of sturgeon entering the fishway would be unsuccessful? Fish were captured in tangle nets downstream so it is possible that the stress of capture and handling caused physiological disturbances that would impede ascent. However, it is equally plausible that the fish that failed to ascend lacked motivation to do so because they were either not mature, not of the appropriate endocrine state, or because they were already engaged in reproduction downstream from the barrier where they were captured. Only after conducting a follow-up study downstream involving radio telemetry, spawning mats for egg collection, and reproductive hormone profiles was it possible to contextualize the findings from the initial efficiency estimates (Thiem et al., 2013). It should be noted that for that study, one of the primary goals was to identify areas of difficulty within the fishway and to generate a preliminary estimate of passage efficiency. The key point here is that efficiency estimates may come from studies with different objectives and hence different study designs. It is therefore possible for the efficiency values to be used out of context. The general transferability of results is a reality for managers. At times, data obtained to address one objective may be all one has to address a different objective.

Any time that experimental approaches are used to inform fishway design, components of efficiency estimates may be biased. For example, in a study of white sucker and smallmouth bass in a river in southern Ontario, Bunt et al. (1999) released fish 100 m downstream from the fishways and did so by alternating releases on both river banks. Although an elegant experimental design for addressing questions of how fish approach a fishway, it does yield two different measures of attraction and passage efficiency. Or in the case of Roscoe et al. (2011) where fish were netted from the top of the fishway, tagged and released downstream. How do those estimates compare to fish that are captured downstream and thus naïve to the fishway? As a manager, which estimate do you use? This is further amplified if you are designing a new fishway where your primary data sources are other studies from different sites, species, fishway configurations, etc. Obviously our point here and with this paper is that an efficiency value should not be taken at face value and must be critically interpreted by the reader. Moreover, the scientific community needs to be more transparent in the limitations with studies and seriously work to improve the reliability of efficiency estimates using the strategies outline below.

6. Improving reliability of efficiency estimates

Here we provide a list of strategies for improving the reliability of fishway attraction and passage efficiency. We further hope that this paper will stimulate the scientific community to devise new and creative ways to improve the reliability of efficiency estimates.

6.1. Need for experimental assessments of efficiency values

Most studies of fishway efficiency involve selecting a single method to estimate efficiency. Use of experimental approaches that contrast different capture techniques, tagging methods, and tracking equipment/methods (among the many other potential sources of variation described here) would be useful for determining the range of variation in estimates that can be attributed to methodological components. Indeed, we are unaware of any studies where the objective is to identify the optimal method for generating efficiency estimates.

6.2. Need to minimize capture and handling stress

All studies require capture of fish and handling for tagging. Recognizing that most capture methods (see Table 1) are inherently stressful and may cause injury is a relevant first step (Cooke and Suski, 2005), but more important is the need to then identify strategies to minimize stress and injury (Cooke and Sneddon, 2007). There is extensive literature on how to minimize capture-related stress and injury (Davis, 2002; Cooke and Sneddon, 2007) which although not specific to fishway assessments, is highly informative.

6.3. Need for use of controls

Several studies have used control sites where no barrier exists to evaluate passage efficiency (e.g., Schmetterling et al., 2002). Use of controls provides important context in terms of identifying some of the issues noted above regarding migratory motivation. For some species, natural failure rate of migrating fish (through difficult and non-difficult sections) can be high (especially for senescing fish such as Pacific salmon; Cooke et al., 2006). Quantifying natural failure rate at a given location would improve the reliability of efficiency estimates.

6.4. Need to use optimal tagging techniques

The science of tagging has developed greatly over the past few decades such that there is much known about the trade-offs associated with different tagging techniques. In addition, best practices have been developed and validated, especially for intra-coelomic implantation (e.g., Wagner et al., 2011). It is worth noting that most tagging validation studies have been focused on economically valuable species. As efficiency estimates are expanded to include at-risk species, the use of surrogates for tagging effects studies can be ill advised (Ebner et al., 2009). Tagging validation studies should accompany any studies that involve new tagging techniques on a species or life-stage that has not previously been studied to identify potential tagging effects that would bias efficiency estimates. Although anesthetics are commonly used for some procedures (e.g., surgery), external tagging and PIT injection may best be done without anesthesia if fish are expected to encounter the fishway shortly (hours to days) after release. A synthesis on the use of electronic tags to assess the fate of fish released by recreational fishers (i.e., Donaldson et al., 2008) contains much information that is directly relevant to tagging fish for fishway studies given similar concerns regarding the potential for tagging to influence behavior and survival. Overall, ideal tagging methods would be rapid, minimally stressful, and be done without anesthesia. Cooke et al. (2012a,b) provide an overview of electronic tagging methods to consider recognizing that the "optimal tagging technique" will vary among species, environmental characteristics of a study system and other constraints.

6.5. Need to consider location of capture and release

In an ideal sense, fish would be captured and released at the same location but sampling (capture) would be spatially stratified. Where possible, fish should not be sourced from a fishway trap. Release should occur sufficiently far downstream (minimum of 100 m) so as to not artificially inflate attraction values. Obviously there is a trade-off in determining what is too close and what is too far. In a recent study, Rio Grande silvery minnow were released at 7 locations up to 19.7 km downstream of a fishway to evaluate effectiveness relative to release site which provides a model for evaluating the influence of release distance on passage success (Archdeacon and Remshardt, 2012).

6.6. Need for multi-year studies with long-life tags

Given the many potential challenges with capturing, handling, tagging, and releasing fish to estimate fishway efficiency, long-term studies across multiple years have great potential to address confounding study effects. Ideally fish would be tagged prior to sexual maturation. However, in doing so it becomes challenging to understand intra-specific variation in motivation (e.g., how do you know in one year whether an individual will migrate or not).

6.7. Need to consider the role of motivation

For iteroparous species, not all individuals may reproduce in a given year (i.e., reproductive holidays). Indeed, some fish may simply lack the motivation to migrate. Knowing the proportion of a population that does not migrate in a given year would refine efficiency estimates. Endocrine sampling to identify the level of reproductive preparedness of fish downstream of a barrier would reveal whether fish are actually motivated to or need to pass (e.g., Thiem et al., 2013). In addition, the extent of partial migration, a phenomenon where some individuals within a population do not migrate (Kaitala et al., 1993), must also be understood to contextualize efficiency estimates. Motivation outside the reproductive period is even more difficult to study as the endocrine basis (e.g., level of reproductive hormones; McKeown, 1984) which is often thought of to be associated with motivation would likely not be relevant. Overall, motivation is potentially one of the greatest drivers of variation in efficiency estimates (and real biological variation in migration) but it also represents one of the greatest challenges for biologists.

6.8. Need to study mechanistic basis of variation in efficiency estimates

When there is significant variation in fishway efficiency among species (or individuals) at a given site, studies of the mechanistic basis for that variation is useful for contextualizing findings and determining the factors that led to the variation. For example, obtaining physiological samples to look at physiological capacity and recovery dynamics (e.g., Pon et al., 2012) or morphological and kinematic studies to identify differences in how fish respond to hydraulic conditions (Kemp, 2012) could reveal why inter-specific and intra-specific variation exists.

6.9. Need for technological validations and multiple tools

Given potential for tag failure, evaluating longevity of tags by retaining some in the laboratory is an approach to improve the reliability of efficiency estimates. In addition, given that system performance (especially detection efficiency) is such a major driver of fishway efficiency estimates, there is a need for extensive testing (to refine system settings and to establish detection probabilities). Once detection efficiency is determined, efficiency estimates can be adjusted to reflect that uncertainty (e.g., Aarestrup et al., 2003). Technology choices should involve consultation with telemetry engineers and where possible should combine technologies to improve the robustness of estimates. Simultaneous continuous monitoring (e.g., Bunt et al., 1999) is favored over sequential monitoring as is the ability to monitor large numbers of fish in spatially confined areas. Use of multiple tools in a single study (e.g., PIT tags for detailed passage efficiency estimates on large numbers of fish, radio tags for detailed fine-scale behavior and attraction efficiency, sensor tags to calculate energetic costs of passage) can also be useful for cross-validating different technologies.

6.10. Need to understand spatial ecology of fish outside of migration window

To determine the need for use of the fishway, a broader study of the spatial ecology of fish outside of the reproduction migration timing window and beyond the region of the barrier would be useful (Cooke et al., 2012a,b). The context provided by such a study would be useful in interpreting efficiency estimates. Indeed, in some systems passage may be important outside of the reproductive window (Baumgartner, 2007). The challenge of course is to understand motivations for passage which are particularly challenging outside of the reproductive period.

6.11. Need to consider individual consequences of passage

In general, once a fish reaches the top of the fishway it is deemed to have been successful. However, if the stress of passage or delays associated with challenges in finding the entrance are too great, mortality after ascending the fishway or sub-lethal fitness consequences could result (e.g., Roscoe et al., 2011). If fishway passage estimates are to be put in the context of riverscapes (Fausch et al., 2002) and integrated watershed management (Heathcote, 2009), there is need to consider whether fish that are successful with passage face any ill effects from doing so.

6.12. Need for studies that combine individual and population level studies

Efficiency estimates are inherently focused on individuals. However, combining estimates of efficiency with broader population-level studies (e.g., using video, fish counters, genetics, DIDSON – and various surveys) would help to contextualize findings. Of late, there has been greater consideration of the ecological consequences of passage, specifically, the notion that fishways could serve as ecological traps (Pelicice and Agosthino, 2008; McLaughlin et al., 2012). Ecological traps in the context of fishways involve the successful upstream passage of adults but where they are then delivered into sub-optimal habitats. For example, a lotic oriented fish that successfully passes a fishway may then be exposed to a vast lentic environment where they are unable to secure food, locate conspecifics or suitable habitat for reproduction, or be exposed to predators. In other words, areas upstream of a dam may not have the necessary environmental and ecological conditions to enable them to complete their life cycle. Given that passage estimates must be considered as only one component of the biological effectiveness, greater attention to determining the instances in which successful passage yields ecological traps is needed. Indeed, Pompeu et al. (2012) suggested that for South American rivers efficiency should be quantified based on the ability of the fishway to maintain viable populations. To do so requires information on population structure downstream and upstream from the fishway, a detailed understanding of reproductive biology/natural history/habitat requirements of the target species, and knowledge of the levels of mixing (i.e., genetic and demographic components) needed to sustain viable populations. Kemp (2012) suggested that there is opportunity for development and application of modeling approaches (including individual-based models and population viability models) to inform decision making that is relevant to entire populations and communities. In addition, Castro-Santos et al. (2009) suggested that by framing fishway studies in the context of 'transparency' (i.e., do fish pass a given area as if the barrier did not exist) can serve as a means to link the concepts of effectiveness and efficiency. In general, more work is needed to understand the ecological need for and consequences of fish passage and how this varies on a global basis.

7. Conclusion

Here we have questioned the reliability of attraction and passage efficiency estimates for conducting biological effectiveness studies of fishways. Although considered the "gold standard", the estimates are not without the potential for bias and generation of values that are misleading or erroneous. Decisions based on efficiency estimates that are inaccurate could be costly for populations and ecosystems, and have socio-economic consequences. By identifying the potential factors that could influence the accuracy and reliability of efficiency estimates, we were also able to suggest strategies for improving their reliability. Beyond the many methodological and technical considerations, we also suggest that there is need for greater transparency in fishway efficiency studies. Every study should provide a candid assessment of what may have influenced efficiency estimates and the rationale for various methodological decisions. Bunt et al. (2012) emphasized the need for greater consistency to enable comparison among studies and we are supportive of that idea. However, we also note that there is a need to revisit the mechanics of how these estimates are generated with greater emphasis on experimental comparison of the role of different capture techniques, tagging strategies, tag types, and tracking technologies to identify optimal study methods. Perhaps of more importance is fundamental work to explore more difficult issues related to inter-specific and intra-specific variation in motivation. Clearly there is need for behavioral ecologists, endocrinologists, and sensory physiologists to work collaboratively in determining the basis for variation in motivation and identifying a simple means by which field biologists can assess it in fish as they are being tagged.

The purpose of this paper is not to discredit previous work. Indeed, in writing this paper we found ourselves being critical of the passage efficiency studies that we have conducted. Almost every efficiency evaluation will have a number of inherent challenges that make it difficult to conduct the optimal study. Nonetheless, it is our hope that this article will stimulate additional research and thought toward improving the study of biological effectiveness of fishways so that the data arising from them is accurate and highly informative for those making decisions that affect conservation outcomes for freshwater fish. As noted by Pompeu et al. (2012), traditional measures of passage efficiency may not apply to all systems such that the time is right to consider redefining how the concept should be defined and measured.

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