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The future of fish passage science, engineering, and practice

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Abstract

Much effort has been devoted to developing, constructing and refining fish passage facilities to enable target species to pass barriers on fluvial systems, and yet, fishway science, engineering and practice remain imperfect. In this review, 17 experts from different fish passage research fields (i.e., biology, ecology, physiology, ecohydraulics, engineering) and from different continents (i.e., North and South America, Europe, Africa, Australia) identified knowledge gaps and provided a roadmap for research priorities and technical developments. Once dominated by an engineering-focused approach, fishway science today involves a wide range of disciplines from fish behaviour to socioeconomics to complex modelling of passage prioritization options in river networks. River barrier impacts on fish migration and dispersal are currently better understood than historically, but basic ecological knowledge underpinning the need for effective fish passage in many regions of the world, including in biodiversity hotspots (e.g., equatorial Africa, South-East Asia), remains largely unknown. Designing efficient fishways, with minimal passage delay and post-passage impacts, requires adaptive management and continued innovation. While the use of fishways in river restoration demands a transition towards fish passage at the community scale, advances in selective fishways are also needed to manage invasive fish colonization. Because of the erroneous view in some literature and communities of practice that fish passage is largely a proven technology, improved international collaboration, information sharing, method standardization and multidisciplinary training are needed. Further development of regional expertise is needed in South America, Asia and Africa where hydropower dams are currently being planned and constructed.

KEYWORDS
dams, ecohydraulics, fish conservation, fish migration, fishway, standardization

1 | INTRODUCTION

Most of the world's rivers have been or are currently being dammed (Nilsson, Reidy, Dynesius, & Revenga, 2005; Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2014). Large dams are primarily used for water storage and hydropower development (Nieminen, Hyytiäinen, & Lindroos, 2016), including in some of the world's biodiversity hotspots (Winemiller et al., 2016); however, large dams are outnumbered a hundred- or thousand-fold (Lucas, Bubb, Jang, Ha, & Masters, 2009) by smaller dams, weirs and barrages for purposes such as irrigation, municipal water withdrawal, flood control, low-flow augmentation, recreation and navigation with large effects on catchment connectivity. Habitat fragmentation of watercourses as a result of impoundment and water control purposes is considered one of the major threats to worldwide aquatic biodiversity, including freshwater fishes (Liermann, Nilsson, Robertson, & Ng, 2012; Nicola, Elvira, & Almodovar, 1996; Poulet, 2007). Fish migrations (synchronized movements by populations or population components driven by the transitory availability and changing location of key resources) (Lucas & Baras, 2001) and dispersal (one-way movement, away from a site as a result of individual behavioural decisions made at different life stages, temporal and spatial scales) (Radinger & Wolter, 2014) in freshwater environments have played an important role in the settlement of human populations (Lucas & Baras, 2001) for purposes such as food consumption, culture and recreation (Nieminen et al., 2016). Given the importance of freshwater fish populations and the many ecosystem services they provide (Lynch et al., 2016), efforts to ensure that fish populations are maintained even in the face of development are critical. Furthermore, fish are a key part of aquatic food webs, strongly contributing to aquatic ecosystem functioning (Lynch et al., 2016). Fish provide the main source of protein and income for hundreds of millions of people worldwide (FAO/DVWK 2002) and many that depend on freshwater fish are impoverished (Bailey, West, & Black, 2015; Cooke, Allison, et al., 2016).

During the course of a lifespan, fish may travel considerable distances between distinct habitats for feeding and growth (feeding migration), refuge from harsh environmental conditions (refuge migration) and/or for spawning purposes (reproductive migration) (Lucas & Baras, 2001). Such movements may occur regularly within an individual's lifetime, may involve a large proportion of the population of a species and may occur at different life stages (Lucas & Baras, 2001). Anthropogenic barriers commonly block or obstruct migration routes, which may strongly affect populations and even the persistence of a species (Radinger & Wolter, 2014). For example, the drastic decline (~75%) of the European eel (*Anguilla anguilla*, Anguillidae) over the past few decades has partly been associated with the mortality of adult eels passing through hydropower turbines during their migration from freshwater feeding grounds to oceanic spawning grounds (Sargasso Sea) (Pedersen et al., 2012). Moreover, there are countless instances where anadromous fish migrations have been blocked entirely by dams that lack upstream fish passage which has resulted in dramatic changes to the upstream fish community and extirpation of some species (Lucas & Baras, 2001). Dispersal by river fishes, however, is also crucial to population processes but is impacted by river fragmentation (Radinger & Wolter, 2014). Construction of engineered in-river structures continues apace in many parts of the world; however, other long-developed areas are restoring river connectivity by removing dams and by providing conduits for the passage of biota, especially fishes (Gough, Philipsen, Schollema, & Wanningen, 2012; Poff & Hart, 2002; Tummers, Hudson, & Lucas, 2016).

Fishways—defined here as any structure deliberately created to facilitate safe and timely fish movement past an obstacle—date back at least several centuries. In the 19th century, fishways emerged as a mitigation effort to facilitate the bidirectional movement of fish around barriers, with perhaps the first fishway built in Pawtucket, Rhode Island in 1714 (Kulik, 1985). We use the terms fishway and "fish pass" interchangeably, although it should be noted that the latter can, sometimes wrongly, imply successful design functionality to some stakeholders. For the past half-century, biologists and engineers alike have been working towards improving fish passage so that the physical structure is rendered "transparent" (Castro-Santos & Haro, 2010) in terms of the effects on target species of fish approaching and passing the facility. Depending on their design, fishways can be classified as: (i) technical structures (pool-type, vertical-slot and Denil fishways, surface-collector bypasses), (ii) nature-like structures (nature-like bypass channels and fish ramps) and (iii) special-purpose structures (eel ladders, fish locks and fish lifts) (FAO/DVWK 2002).

The rate of construction of fishways has increased in recent decades; however, the performance of passing fish through these structures remains low in many regions (Bunt, Castro-Santos, & Haro, 2016; Nieminen et al., 2016; Noonan, Grant, & Jackson, 2012; Roscoe & Hinch, 2010; Williams & Katopodis, 2016). Reasons for this failure are unclear, but lack of biological knowledge and flaws in construction and/or operation of fishways are likely two major causes (Kemp, 2016). Furthermore, although fishways facilitate passage of migrating fish, several unintended ecological consequences can arise and subsequently compromise the sustainability of fish populations and influence metapopulation dynamics (McLaughlin et al., 2013). Here, we apply an interdisciplinary approach using aspects of fundamental and applied science to identify key questions in the field of fish passage and fish conservation. We summarize the roles of different research fields contributing to fish passage research, evaluate what fundamental knowledge and tools are required to implement effective fish passage solutions, explore promising new approaches to better support natural fish movements in catchments impacted by humans and propose measures needed to facilitate information exchange and regional training in fish passage to minimize impacts on fisheries in the face of development. With this, we provide a roadmap to support a more effective, productive and realistic approach to how fishways can support fish passage in the face of continued development.

2 | FUNDAMENTAL SCIENCE UNDERPINNING APPLIED FISHWAY RESEARCH

Any effort to prioritize research in support of a conservation goal must begin with a clear definition of that goal. Broadly speaking, the primary objective of fish passage is to promote healthy aquatic ecosystems through restoration or maintenance of ecological connectivity. Successful fish passage conserves native diversity and nutrient flux between and among lacustrine, riverine and marine environments; it does this by eliminating or minimizing barriers to movement (Hall, Jordaan, & Frisk, 2012; Naiman, Bilby, Schindler, & Helfield, 2002).

But what is a barrier? From an ecological perspective, a barrier may be considered anything that retards the movement of organisms between habitats. For fish, barriers can be physical, such as a hydroelectric dam (artificial barrier) or a rapid, reservoir or waterfall (natural barrier), but could also be hydraulic (e.g., high velocities or low water depths), chemical, thermal or even just a matter of distance. In the context of fish passage, we typically think of barriers as localized structures within the river continuum; however, barriers may have greater dimensionality. For example, an impoundment where flow cues are reduced may act as a barrier by decreasing the rates at which migratory fish arrive at spawning or feeding habitat. We can expand the barrier concept to include anything that imparts a change (typically a reduction) in fitness during and following passage (Castro-Santos, Cotel, & Webb, 2009). Barriers can simultaneously reduce survival, movement rates and speed, and increase fitness costs (Caudill et al., 2007; Nyqvist et al., 2016; Venditti, Rondorf, & Kraut, 2000; Jepsen et al., 1998). Of course, these considerations outline the main goals of fish passage: to achieve diverse fisheries management objectives related to upstream–downstream connectivity that encompass biological, cultural and socioeconomic components.

The range of study disciplines relevant to fish passage reflects the processes of fish movements in river catchments, responses to altered environments and the socioeconomic implications for fisheries. Both biology and hydraulics are fundamental to fish passage research and development, as understanding responses of biota to altered flow is central to all aquatic life, including fishes. Indeed, this is particularly true given the changes to river flows and the effects that climate change may have on those flows and on the design and use of fishways. Flow regulation and impoundment affect numerous life stages, including the migration and the dispersal period. Such impacts are likely to be exacerbated by climate change through changes to the hydrographic conditions during migration periods (Gauld, Campbell, & Lucas, 2013). Research is needed in future-proofing fish passage solutions to altered climate conditions, complicated by the large range of likely hydrological responses across the globe, and by local hydrological processes within river basins. For example, warmer river conditions and higher flows may influence energy use and limit fish swimming capacity during their migrations and particularly as they approach and interact with fish passage facilities (see Rand et al., 2006; Zabel, Burke, Moser, & Caudill, 2014). The fishway of tomorrow may need to be "easier" for fish to traverse if environmental conditions constrain fish swimming activity.

Physiology, including biomechanics, kinematics and energetics, is also key to fish passage science, engineering and practice (Bainbridge, 1960; Castro-Santos & Haro, 2006; Cooke & Hinch, 2013; Katopodis and Gervais 2012; Silva et al., 2015; Stringham, 1924). Historically, there has been an emphasis on fish swimming performance to provide a template for which to design and engineer fishways. Recently, studies have shown that most of the literature on swimming performance derived in the laboratory may underestimate actual abilities of free-swimming fish (Castro-Santos, Sanz-Ronda, & Ruiz-Legazpi, 2013; Peake, 2004; Tudorache, Viaenen, Blust, & De Boeck, 2007). New methods have improved accuracy and are currently being replicated worldwide (Haro, Castro-Santos, Noreika, & Odeh, 2004; Sanz-Ronda, Bravo-Córdoba, Fuentes-Pérez, & Castro-Santos, 2016). But performance in relation to fish passage, which can be generally classified in terms of endurance, motivation and distance traversed (Brett, 1964; Haro et al., 2004), has to be re-evaluated.

Animal behaviour explains how animals function within their physiological limits in response to different environmental conditions (Lauder, 2000), and although it is one of the most important fields of biology that limits fish passage performance, it is one of the least studied areas of fish biology. Lack of knowledge in this area has limited the ability to design effective fishways for different species. One aspect of behaviour that can determine passage success is motivation, which can be quantified as rates of movement and duration of effort (Goerig and Castro-Santos 2017; Castro-Santos, Shi, & Haro, 2016).

Measures of fish movement should be quantified using units of distance per unit time; in the case of passage through a barrier, however, units of per cent passage per unit time are more meaningful (see Standardization of fish passage evaluation subsection for more details). These metrics must in turn be coupled with appropriate statistical methods (e.g., survival analysis method and multistate Markov models) that quantify the response variables in ways that are relevant to the objective of maximizing rates of movement. Increasingly powerful applications of survival analysis methods allow for this (Castro-Santos & Perry, 2012). Key to the success of this approach is the recognition that passage is not a discrete binomial or multinomial response, but instead the outcome of continuously competing processes.

Due to the overlap between complementary research fields for the development of fish passage, interdisciplinarity has been increasingly evident, for example in the fields of ecohydraulics and ethohydraulics. Fishway engineering also borrows from the field of "mimetics" in which characteristics of natural systems are engineered or synthesized (FAO/DVWK 2002; Jungwirth, 1996). Operational research methods are increasingly being combined with geographical information systems of barrier distributions to plan how best to apply fish passage solutions at existing barriers (King, O'Hanley, Newbold, Kemp, & Diebel, 2017; McKay, Schramski, Conyngham, & Fischenich, 2013; Neeson et al., 2015), and to decide how to plan future, more eco-friendly hydropower development (Ioannidou & O'Hanley, 2018).

The multiple disciplines of expertise surrounding fish passage research and development are dominated by the natural and physical sciences, but there is increasing recognition of the importance of incorporating social science and economics practices into current and future management approaches to river connectivity problems for fish and other biota. Although fishways usually form a small capital cost of water development schemes, if they do not work as they should, or if wider ecosystem services are severely compromised, that can represent a substantial long-term cost to the natural capital of the ecosystem. Consequently, more effective economic and non-market valuation of ecosystem goods and services (Khai & Yabe, 2014; Nieminen et al., 2016) must play an increasing role in evaluating the long-term options for effective connectivity maintenance and restoration. Similarly, the continued development of social science approaches for determining and reflecting socio-cultural values and needs, including those of local communities, deserves consideration in the fish passage sphere, which begins with identifying fisheries management objectives for a given river.

3 | THE MISSING PIECES: KNOWLEDGE AND TOOLS NEEDED

3.1 | Spatial and temporal context of fish migration and dispersal

Until recently, fishway science has concentrated on the fishway(s) and barrier(s) and fish throughput at a site-specific scale and has been complemented by laboratory studies of swimming performance (Clay, 1995; Larinier & Marmulla, 2004). Downstream passage impacts, however, have been largely overlooked by researchers and natural resource managers, particularly outside of North America (Aarestrup, Jepsen, & Rasmussen, 1999; Aarestrup & Koed, 2003; Jepser et al., 1998). Prior to 1995, and often still today, the emphasis of site-specific studies was on recording fish within and/or exiting the fishway, usually by direct sampling of fish or use of fish counters, at the expense of considering passage as a process or mechanism relating to individual behaviour of adaptive value (Burnett et al., 2017; McLaughlin et al., 2013; Roscoe & Hinch, 2010). Even today, the description of the full migration systems and timing in well-studied species of salmonids remains incomplete (Aarestrup, Birnie-Gauvin, & Larsen, 2017; Winter, Tummers, Aarestrup, Baktoft, & Lucas, 2016). Fuller consideration of the adaptive value of fish movement, including passage at an obstacle, requires broader spatio-temporal context (fine-scale to landscape-scale; Fausch, Torgersen, Baxter, & Li, 2002). For example, what are the main macroscale catchment responses to flow alteration or altered population distribution? What are the behavioural and physiological responses to local hydraulic (and other) conditions that reflect decision-making processes by fish—continuation or rejection of a path, for example within a fishway? Such a perspective must operate at multiple temporal scales, from the timescale of behavioural decisions, second by second, to the much longer timescales of population dynamics and resilience, to socioeconomic decisions, payback and environmental alterations that may arise in relation to river engineering projects.

3.2 | Biodiversity conservation and ecological resilience

Rivers are also well-defined boundaries and corridors for the spatial and temporal distribution of nutrients, energy and matter, which determine biological activity across the landscape. Materials and energy may flow across the landscape as organic and inorganic matter or packed as organisms (fish, invertebrates, etc.). This is the case for Pacific salmon (*Oncorhynchus* spp, Salmonidae), in which more than 95% of the body mass is accumulated from the marine environment and deposited in freshwater habitats during spawning and death, providing an important nutrient subsidy to freshwater environments (Gresh, Lichatowich, & Schoonmaker, 2000). The linkage between nutrient flow to freshwater ecosystems and community dynamics has been evident through increased production of aquatic invertebrates and fish observed in rivers and streams with higher carcass abundance or live salmon (Naiman et al., 2002). The flux of biotic (e.g., fish, invertebrates, microfauna) and abiotic vectors (that actively transport matter or energy across the landscape, Puth & Wilson, 2001) within ecosystems, communities and populations is therefore essential for ecosystem function. This ecological dynamic is vulnerable to human alteration of the landscape that disrupts (Harris & Scheck, 1991) and creates new ecological boundaries and corridors (Bennett, 1991). We suggest that managers and researchers need to develop effective measures that permit these fluxes.

To date, there has been an overemphasis on facilitating and monitoring fish passage for a few species. On one hand, this is understandable; concentration on economically important fish stocks for which long-distance migrations are a part of the life cycle (e.g., anadromous salmonids; Williams, 1998; Nieminen et al. 2016) is always likely to be a first priority. And yet, restrictions to the free movement of other native fishes (and other biota, including invasive species) influence the entire community and resultant ecological interactions (McLaughlin et al., 2013). Such a bias has tended to result in economically valuable fishes (e.g., salmonids) becoming target species, with research efforts and practical applications concentrated on them to increasing effect (Bunt et al., 2016; Noonan et al., 2012). However, it has generated a biased perspective of the suitability of fishway solutions for a wider range of species and life stages. For example, the predominance of technical upstream fish passage designs suited mostly to salmonids, as detailed in Clay (1995), did little to solve passage problems for the large numbers of catadromous, potamodromous and amphidromous migrants in catchments where they are abundant (Lucas & Baras, 2001). Fifty-five per cent of 181 fish species in Canadian freshwaters have been described as migratory (38% diadromous, 62% potamodromous, Lucas & Baras, 2001); however, a detailed understanding of the migration behaviour and capacity is known for less than a third of these species. Knowledge concerning the importance of migration and dispersal phases in the life histories of tropical and subtropical freshwater fishes is far lower (Baras & Lucas, 2001) due to the extraordinary diversity that is present in those riverine systems, although rapid progress is being made in some regions (Araújo-Lima & Ruffino, 2003; Baumgartner et al., 2012; Makrakis et al., 2012). Such information is urgently needed, as river obstruction is the single most pervasive threat to the functionality of freshwater systems worldwide.

It has taken a paradigm shift to introduce more suitable fishway designs for a wider range of native fishes in, for example, Australia (Stuart & Mallen-Cooper, 1999) and Europe (Jungwirth, 1996), but major problems in achieving functional connectivity still exist for the majority of species and in many regions (Foulds & Lucas, 2013; McLaughlin et al., 2013; Pelicice, Pompeu, & Agostinho, 2015). One key target of river restoration is to recover more natural ecological processes, often through encouraging greater biodiversity and the associated ecological resilience (Palmer et al., 2005). This may necessitate recolonization by species that were lost. Here, fish passage solutions need to facilitate bidirectional movement of the vast majority of the native fish community, and not just obligatory migrants (Tummers et al., 2016). The EU's Water Framework Directive states that progress towards "good ecological status" in impacted waterbodies needs to be achieved relative to reference assemblage conditions. Solving this requires an understanding of how small, poorly dispersing fish as well as classic migrant species and strong dispersers can be facilitated in their passage of obstacles (Gibson, Haedrich, & Wenerheim, 2005; Macdonald & Davies, 2007; Pépino, Rodríguez, & Magnan, 2012; Warren & Pardew, 1998) and requires a further paradigm shift in attitude concerning fish passage (Tummers et al., 2016). This links back to the need to determine better how fishways or bypasses for biota more generally can enable the ecological flux of nutrients, energy and matter within aquatic systems so as to recover biological activity, biodiversity and ecological resilience.

3.3 | River connectivity: fish passes vs. dam removal

Inland fish and fisheries are important to human health and well-being (food security; economic security; empowerment; cultural services; recreational services; human health and well-being; knowledge transfer and capacity building) and to the environment (ecosystem function and biodiversity, environmental indicators for global change) (Lynch et al., 2016). River restoration efforts are increasing across the developed world, and improving longitudinal connectivity for river processes is a fundamental element of this effort (Fausch et al., 2002; Gough et al., 2012; Kemp & O'Hanley, 2010). Thus, it is imperative to consider and evaluate all the ecosystem services associated with restoring connectivity. Complete or partial physical removal of obstacles reinstitutes a greater proportion of natural processes (Garcia de Leaniz, 2008; Poff & Hart, 2002) than provision of a fishway(s) which is, at best, a mitigation measure (Brown et al., 2013; Kemp, 2016; Roscoe & Hinch, 2010). Hence, the context of effective fish passage, and new research, needs to be better integrated into the full range of methods for improving longitudinal and also lateral connectivity, the latter of which receives too little attention in conventional fish passage research, but is of great importance from a restoration perspective (Bolland, Nunn, Lucas, & Cowx, 2012; Cooke, Paukert, & Hogan, 2012). Fish migration is commonly a bidirectional (upstream-downstream) process (notwithstanding insufficient consideration of passage in the lateral trajectory in floodplain rivers, giving a second axis of movement). To date, there has been too much emphasis on upstream passage which is largely the domain of adults and stronger swimming species, and too little on downstream and lateral passage, which may involve passively drifting eggs and larval stages (Aarestrup & Koed, 2003; Bolland et al., 2012; Calles & Greenberg, 2009; Jepsen et al., 1998).

A much better understanding is needed of the space-use requirements of freshwater and diadromous fishes by part or all of a population (Cooke, Martins, et al., 2016) to provide sound advice for appropriate fish passage solutions. Similarly, river restoration, including dam removal and fishway provision, would benefit from better landscape-scale tools (and their take-up) for options appraisal (see Box 1 for an example of the impact of barrier removal on restoration of lowland rivers in Denmark). Although a costly exercise, dam removal is becoming increasingly common in some places (US: Brown et al., 2013; Denmark, Birnie-Gauvin, Larsen, Nielsen, & Aarestrup, 2017a). Following the removal of the Elwha Dam in Washington (USA), Tonra, Sager-Fradkin, Morley, Duda, and Marra (2015) reported returns of Pacific salmon immediately following removal. More time is needed to determine the extent to which these measures result in fisheries recovery. Dam removal, however, requires consideration of more than offsets for any power generation lost. Cost-benefit analyses of removal will require considerations of sediment and contaminant release, impacts on downstream hydrology, and changes to the status of the local fish community.

Box 1

Providing effective fish passage solutions may not be enough to promote population sustainability in some migratory fish species. While it restores longitudinal connectivity, most of the methods currently employed to establish fish passage do not consider the habitat loss resulting from the presence of weirs and dams. This may be a particular problem in lowland streams, where gradient is often a limiting factor for rheophilic habitat, the preferred habitat for iconic salmonid species such as brown trout (*Salmo trutta*, Salmonidae) and Atlantic salmon. Although a general negative correlation between the number of weirs and the density of juvenile salmonids exists in Denmark (Kristensen, Jepsen, Nielsen, Pedersen, & Koed, 2014), this relationship considers impacts from both habitat and connectivity loss. The typical inundated zone upstream of a weir or dam contains conditions not reconcilable with the requirements for salmonid spawning and juvenile habitat, thus limiting reproduction and productivity. Traditional fishways (Poff & Hart, 2002; Quiñones et al., 2014) are increasingly found to be of limited efficacy (Bunt et al., 2012), leading to the current practice of constructing nature-like fishways. The efficiency of such bypasses is rarely tested under natural conditions (however, see Aarestrup, Lucas, & Hansen, 2003). Few peer-reviewed empirical data sets exist on the effectiveness of these bypasses to promote fish passage, though the general belief is that natural-like fish passes give more effective restoration of rivers. Nevertheless, neither traditional fish passages nor nature-like fishways resolve the problem of lost natural gradient due to weirs and dams. Because lowland rivers naturally offer limited drop, the reproductive and productivity potential of salmonids in these rivers is restricted by weirs and dams (Birnie-Gauvin, Aarestrup, Riis, Jepsen, & Koed, 2017b). We suggest that it is of paramount importance that we reinstate more natural gradients to recover the lost habitat in order to conserve and promote the sustainability of salmonid populations. Realizing this problem in Danish lowland streams and rivers has led to the suggestion that barrier removal and restoring the natural gradient is a go-to mitigation tool where possible, especially when structures no longer serve a purpose. Such barrier removals have already begun, and initial results are promising both on a site and river scale (Candee, 2016; Birnie-Gauvin, Larsen et al., 2017).

In general, a global reliance on dams for flood control, irrigation, potable water and hydropower means that more barriers are being constructed than removed. Under such a scenario, there will always be a need to make provision for fish passage, and better catchment planning of barriers is undoubtedly also needed (Winemiller et al., 2016). Great strides have been made in the development of models for planning catchment connectivity benefits and economic effects in relation to barrier addition or removal (Kemp & O'Hanley, 2010; McKay et al., 2013) but more can and is being performed to improve this by making such tools more accessible, biologically relevant and user-friendly (King et al., 2017) to river managers internationally.

Due to the large initial capital cost of constructing fishways, we need a better understanding of their ability to meet the objectives compared to alternative outcomes, including doing nothing or physically removing a barrier. Far too often, the costs of doing nothing, in terms of lost jobs, income, food security and other losses in ecosystem services outweigh the capital required to construct a fishway or remove the barrier. Few high-quality studies have evaluated fishway performance outcomes (Bunt, Castro-Santos, & Haro, 2012; Bunt et al., 2016; Cooke & Hinch, 2013; Nieminen et al., 2016; Noonan et al., 2012; Roscoe & Hinch, 2010). Far too often, fishways are seen as capital expenditure projects, the likely effectiveness of which does not need to be tested beforehand or in a substantial number of cases, evaluated afterwards (Cooke & Hinch, 2013). Considering that many hundreds of fish species (and other animals) rely on free movement in rivers for life-cycle completion and that there are many different combinations of fishway types and gradients, a few quantitative, well-designed studies is wholly inadequate to make sound conclusions on their performance for all but a few species and fishway designs (Bunt et al., 2016; Noonan et al., 2012; Williams & Katopodis, 2016). Consequently, this has resulted in past errors of, for example, using salmonid-appropriate fishway designs for non-salmonid fish communities (Mallen-Cooper & Brand, 2007). Research on fish passage design solutions often lacks rigorous testing, and a relatively small proportion is subjected to peer review. Better evidence and education are needed for river managers and stakeholder groups of the efficacy of fishway designs, their limitations and alternatives, not only at large dams but also for small, but abundant structures (Gibson et al., 2005). Finally, in addition to the problems identified above, there is no scientific basis to assume that a single fishway design will provide adequate conditions to pass a large number of species with different physiological characteristics, swimming abilities, body size and behaviours (Bunt et al., 2012, 2016). Effective passage for several migrant fish species at a dam may involve installation of two or more fishways of differing size and hydraulic characteristics.

3.4 | Standardization of fish passage evaluation

Overall, there is a need for stronger rationales supporting targets and criteria for what constitutes "acceptable" fish passage performance (Cooke & Hinch, 2013; Lucas & Baras, 2001; Roscoe & Hinch, 2010). Despite substantial literature on fish passage impacts at barriers and fishway designs, there are few objective targets or recommended performance criteria published. We highlight that researchers and natural resource managers are to blame here. How can we seek sufficient benefits from mitigation efforts or achieve effective restoration if we have not managed to set appropriate performance criteria?

It can be argued (*sensu* McLaughlin et al., 2013) that fishway performance is specific to the context of a particular location—for example, in terms of the societal outcomes—but few local, quantitative catchment targets have been published. This represents a missed opportunity, because each fishway can be viewed as a natural experiment, and coordinated efforts to perform evaluations within a consistent and rigorous framework hold great potential for identifying key factors that lead to passage success or failure (Castro-Santos & Haro, 2010). The same authors proposed the concept of "transparency" in terms of negligible fitness costs for the ideal fishway. Lucas and Baras (2001) recommended attraction and passage efficiency targets of 90-100% for diadromous and strongly potamodromous fishes, recognizing the cumulative impact, through reduced net passage across multiple sites, for effective restorative or population maintenance. But predicting or demonstrating fish population or assemblage responses to improved fish passage at obstacles remains poorly resolved, with only a few notable exceptions (Harris & Hightower, 2012). Surely if cumulative barrier construction provides a proportional disbenefit for fish, then coordinated cumulative fishway construction can provide compounded benefits. Although in these cases, if critical habitats (e. g. reproduction sites or nursery areas) are not maintained, the construction of fishways will be insufficient at preserving fish populations (Pompeu, Agostinho, & Pelicice, 2012).

With regard to quantifying passage processes, there are inconsistencies in definitions and methods used to gather and analyse data on fishway performance (Kemp, 2016). Given the high cost of individual empirical studies and the value of resultant data, the current lack of common standards can limit the utility of those data for meta-analyses and discovery of emergent patterns from these data (Bunt et al., 2016; Noonan et al., 2012; Roscoe & Hinch, 2010; Williams & Katopodis, 2016). Washburn, Hateley, and Gregory (2015) outline a European standard for fishway evaluations that is currently under development, which would facilitate compilation and use of such data in meta-analyses. That being said, care is needed to avoid curtailing innovation, and not preclude the use of relevant methods and data because they fail to meet a (potentially) narrowly defined standard. Generally, it is agreed that the appropriate methods should be used that can measure the rate of encounter and path of individual fish (of particular species, life-cycle stage and size) at an obstacle, relative to reference conditions, and whether subsequent passage is successful, so that key efficiency metrics of approach, entrance and passage can be measured (Cooke & Hinch, 2013), preferably with respect to time elapsed to each event for each fish (Castro-Santos & Haro, 2003; Castro-Santos & Perry, 2012).

Castro-Santos et al. (2009) proposed a suite of biological, structural and hydraulic covariates that should be reported for each site and laid out a conceptual framework based on movement theory that provides standardized metrics and objective measures of fish passage effectiveness while explicitly accounting for the complex behavioural and site-specific features that often confound efforts to measure performance.

To understand this complexity, and its appropriate solution, one must first recognize that passing a barrier (upstream or downstream) requires that fish approach, enter and pass the fishway (Figure 1 and Table 1). Each of these is a discrete task that can be thought of as a different state or phase through which the fish must pass, each one

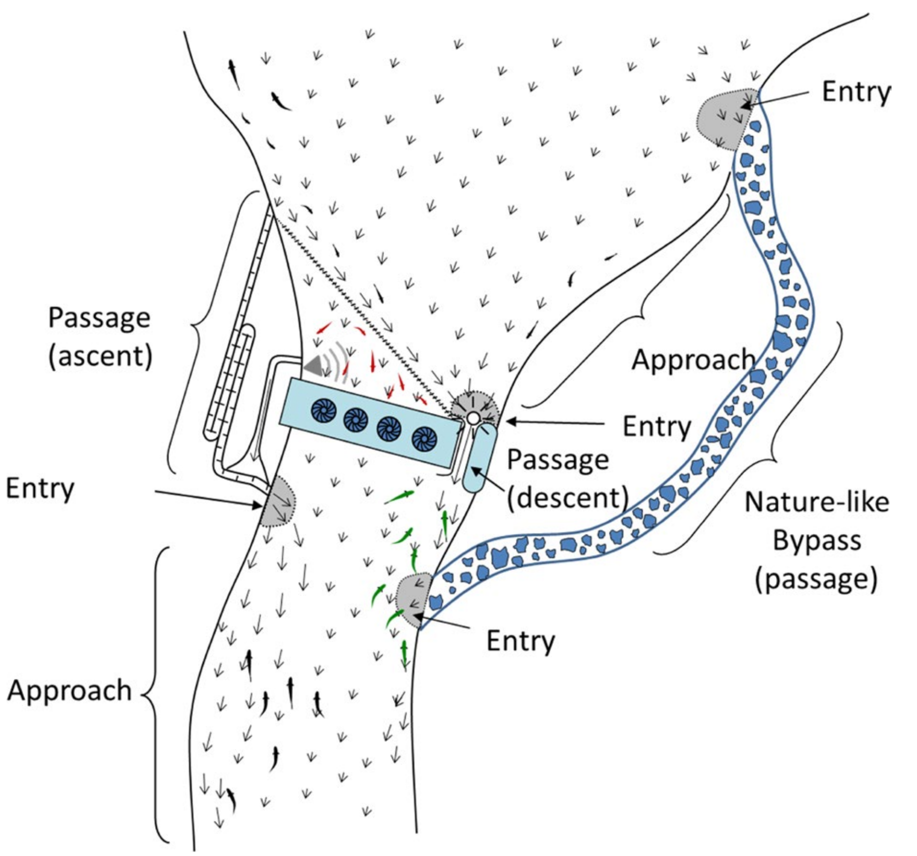

FIGURE 1 Phases of fish passage applied to any obstacle with fishway(s), herein illustrated for a powerhouse equipped with separate up- and downstream fishways (adaptation of Castro-Santos & Haro, 2010) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary of key considerations for assessing fishway performance. The text used refers to ascent of a fishway, but could equally be applied to descent

Consideration	Definitions	Units	Rationale	Methods	References
Barrier passage time	*Conditional passage and failure time:* both passage and failure times should be considered simultaneously, with time to pass censored at the last extant effort for fish that fail to pass, and time to fail censored at time of passage for fish that successfully pass. Data can be presented as survivorship functions (e.g., Kaplan–Meier curves) or as cumulative incidence functions (the sum of the competing risk functions). Where possible, these rates should be calculated within each stage of passage (Approach, entry, internal passage), but can also be calculated over the entire passage process. *Approach time:* time spent in the dam forebay or ponded area upstream (downstream migration) or obstacle tailrace (upstream migration). *Entry time:* time spent near a fishway entrance (upstream or downstream), where it is assumed the fish is able to detect and respond to the flow or other physical features associated with the structure. *Internal passage time:* time spent within the fishway on a given passage attempt (and/or cumulative across attempts). *Transit time:* Time required to ascend a fishway in a single effort. This is the difference between the last observation at the fishway entrance to the last (or sometimes first) observation at the top on a given attempt and is an estimate of the mean associated with passage for each fish	Cumulative proportion passing (or rejecting) before a given time	The rate at which fish approach and pass a barrier, coupled with the rates at which they abandon their efforts determine overall per cent passage, and can have important consequences for fitness and survival	Telemetry and time-to-event analysis	(Castro-Santos, Shi, & Haro, 2016; Castro-Santos & Perry, 2012; Castro-Santos et al., 2009; Crowder 2012; Pintilie, 2006)
Barrier passage rate	*Conditional Passage and failure rates* These are transformations of the cumulative proportion passage described in the previous cell. In this case, however, the rate is calculated on each timestep, considering only those fish that remain available to either pass or fail within that timestep	Proportion of available fish passing (or failing) on a given time interval			
Per cent passage	*Per cent passage* has intuitive value to understanding fishway performance. Recognizing the bias that can be incurred by ignoring variable exposure duration to each zone. We suggest the following components be measured: *Proportional arrival (or discovery):* the proportion of migrants arriving to a hydraulic or other physical signal that indicates the presence of the fishway entrance or at the base of a barrier to fish movement and near enough to a fishway entrance for fish to detect fishway attraction flow. *Per cent Entry:* Per cent of tagged fish attracted to the facility that enter the fish passage structure. *Internal Per cent Passage*: commonly calculated by dividing the number of fish of a species that exit a fishway by the number that are detected at the fishway entrance. *Per cent Passage:* In the presence of a single passage route, this is the cumulative proportion of all three percentage elements described above	Individual to population	The percentage of individuals that are attracted to, enter and ascend a fishway are important for understanding the impacts of migration barriers and dam operations on individuals and populations	Telemetry and electronic fish counters	(Aarestrup et al., 2003; Bunt, Katopodis, & McKinley, 1999; Bunt et al., 2012; Cooke & Hinch, 2013)

associated with a distinct zone. During the approach phase, a fish occupies a migratory state ("approach") where it approaches the barrier and encounters physical signals that identify the location of the fishway. Having detected a possible passage route, it now enters the "entry" state. During this phase, the fish is able to detect and respond to the entrance and must make a decision whether to enter the structure. Finally, having entered, the fish occupies the "passage" state, where it must now pass through it. Success or failure to advance through any one of these states may occur for a number of reasons, including physical capability and behavioural rejection. Taken together, the overall probability of passage is the product of these three steps:

$$P_{\text{tot}} = \prod_{i=A}^{P} P_i, \tag{1}$$

where the probability of successfully passing the barrier (P_{tot}) is the product of the probability of passing through each of the three states (i = A [approach], E [entry], and P [internal passage]). Studies that fail to differentiate among these three components of passage risk falsely attributing passage success or failure to only one of them. By monitoring each state independently, it is possible to attribute passage success or failure to its appropriate zone (Castro-Santos, 2012; Castro-Santos & Haro, 2010).

Fish passage is further complicated by the fact that individual animals may vary in their exposure to the different zones, either due to changing environmental conditions and/or variable duration of effort and exposure to each of the zones. As a result, the values of P_i cannot be described by simple binomial or multinomial metrics, as is commonly performed, but instead must include a time axis: the probability of passage in zero time is zero, but it increases with time (Castro-Santos, 2004). Because of this, the amount of time spent attempting to pass is another key element that must be measured and controlled for, and to avoid bias, passage must be measured as a time-based rate, not a simple proportion.

Of course, the number of different scenarios related with upstream or downstream fish passage is nearly endless, with varying exposure durations and behaviours seemingly precluding objective analysis. This is further complicated because fish not only move forward through these states—from within each state a fish may also fall back into a previous one, at which point it is no longer available to move forward from that state. This process by which the occurrence of a given event precludes the opportunity to experience an alternative event is called "competing risks," and an entire field of statistics exists that was developed specifically to address this type of situation (Castro-Santos & Haro, 2003; Castro-Santos & Perry, 2012; Crowder, 2012; Pintilie, 2006). Commonly referred to as "survival analyses" (we prefer to use "time-to-event" analyses to avoid confusion with actual survival studies), these methods were largely developed in support of medical trials to measure rates at which events occur while controlling for competing events that might otherwise bias results. Using this approach, individuals are included in the "risk set" for the entire duration of their exposure to a given condition. The risk set can be thought of as the denominator of a rate expression, where a proportion is being measured continually over time. When events occur, the proportion of the risk set that each event represents is registered, along with the amount of time it took for the event to occur, producing a rate estimate. When an individual leaves the risk set, however (e.g., enters and passes a different fishway or abandons the approach zone), it is considered "censored" and is removed from the denominator (risk set). In this way, individual exposures are quantified and accounted for while avoiding bias induced by variation in duration of effort (Castro-Santos & Haro, 2003; Castro-Santos & Perry, 2012; Hosmer & Lemeshow, 1999).

One appealing aspect of using time-to-event analyses is that it allows for explicit control of covariates that change over time (Allison, 2010; Castro-Santos & Perry, 2012; Zabel et al., 2014). Event times are calculated from time of entry into the risk set, but individuals can experience multiple censoring events within the time course without incurring pseudoreplication. Rates are calculated within intervals that can be set to whatever timestep is deemed appropriate for a given study (governed by, for example, diel period or hourly measures of discharge). An added attractive feature of this approach is that it allows for explicit recognition of the fact that individuals and species may vary with respect to migratory motivation (Goerig & Castro-Santos, 2017). The censoring approach only calculates movement rates for individuals that are trying to pass.

This framework simultaneously resolves two key components of passage, which are the probability of passage and the delay incurred while trying to pass. The output of the technique produces estimates of entire probability functions, allowing estimates of how long it takes for a given proportion of a population to pass, while at the same time removing bias from estimates of rates associated with different operational and experimental conditions. Passage should thus be quantified as a rate (per cent passing per unit time) (Table 1). This also provides a basis for performance requirements that might include both proportion and temporal elements, for example requiring passage of 85% of the total population, with 50% passing in less than 2 days (Castro-Santos et al., 2009).

Telemetry is an important method for determining fishway approach, entry, passage rates and post-dam passage behaviour and survival, as individual remote identification is possible at multiple locations, with fine temporal resolution (Castro-Santos et al., 2009; Cooke & Hinch, 2013; Cooke, Hinch, Lucas, & Lutcavage, 2012) (Table 1). Choice of telemetry method for fishway performance studies is dictated by the site, local environment, fish availability and available funding (Cooke & Hinch, 2013). However, one immediate need is to monitor a larger number of individuals from a wide range of species and sizes simultaneously at a site. Passive integrated transponder (PIT) telemetry offers a good solution, at low cost, and for assessments approaching the fish community level. Currently, this information is almost entirely absent from the literature (but see Baumgartner, Boys, Stuart, & Zampatti, 2010; Lucas, Mercer, McGinty, & Armstrong, 2000; Thiem et al., 2013 for exceptions). Major problems also remain in evaluating passage attempt rates for facultative rather than obligate migrants, as a variable proportion of the former may not be motivated to migrate under the current passage regime relative to a reference state (Kemp, 2016; Goerig and Castro-Santos 2016).

TABLE 2 Considerations for understanding ecological and population impacts of fishways

Consideration	Definitions	Units	Rationale	Methods	References
Biomechanisms	*Biomechanisms:* Underlying physiological, behavioural responses to environmental effect(s)	Individual	Understanding biomechanisms that influence passage rates and times, survival and fitness will help identify solutions for future fishways	Behavioural and physiological evaluations, telemetry	(Burnett et al., 2014; Caudill et al., 2013; Pon, Hinch, Suski, Patterson, & Cooke, 2012; Silva et al., 2015; Thiem et al., 2016)
Population impacts	*Population impacts:* Any changes or responses in the entire population that can be attributed to the fishway, compared to reference conditions with or without impoundment. Observed changes may occur over time or between two time periods and may include genetic, life history, numerical or changes of any combination of the above	Population	Understanding population-level impacts will help determine the numerical impact on the population and can be used to model the effects of migration barriers on population dynamics	Electronic fish counters and large-scale tagging studies	(Burnett et al., 2017)
Pre- and post-obstacle passage effects	*Carry-over effects*: when an individual's previous experience explains their current performance	Individual to population	Carry-over effects can influence physiology, behaviour, growth, reproduction and survival post-dam/obstacle passage	Behavioural and physiological evaluations, telemetry	(Burnett et al., 2014; O'Connor, Norris, Crossin, & Cooke, 2014; Roscoe et al., 2011)
	Intergenerational effects: when a parent's exposure to a stressor(s) influences the life history and phenotype of their offspring	Individual to population	Maternal exposure to a stressor can influence the life history, size, behaviour and performance of offspring	Experimental maternal exposure to chronic stressors	(Braun, Patterson, & Reynolds, 2013; Sopinka et al., 2017)
Study design	*Tagging and handling effects:* any effects on fish responses associated with attaching tags on physiological state, behaviour, reproduction or survival, or any effects on fish responses associated with the capture, holding, transport	Individual	Tagging and handling can influence fish behaviour (e.g., feeding, growth, swimming performance, social interactions), physiology, survival, health (e.g., infection around incision site), susceptibility to predation and catch, and Darwinian fitness	Laboratory- and field-based experiments of tag effects (e.g., tag types, tagging procedures) and handling effects (e.g., capture, transport, blood sampling, non-lethal biopsy)	(Cooke & Hinch, 2013; Jepsen, Thorstad, Havn, & Lucas, 2015 Lucas, 1989; Sharpe, Thompson, Lee Blankenship, & Schreck, 1998)
	Management experiments: in the context of fishways, management experiments are any experimental design that involves manipulation of dam operations	Individual to population	Management experiments are focused on "learning by doing." Studies with suitable design, monitoring approaches and funding can inform "best management practices" that reduce the impacts of barriers on aquatic ecosystems. Achievement of suitable passage conditions requires adaptive management	Experimental flow releases in combination with telemetry to determine individual and population effects, and electronic fish counters	(Burnett et al., 2017; Memmott et al., 2010; Olden et al., 2014; Poff et al., 2003; Richter, Mathews, Harrison, & Wigington, 2003; Walters & Holling, 1990)
	Uncertainty can take two forms: *Process error:* random variation in survival or behaviour due to process such as stochastic environments. *Observation or measurement error:* variation attributable to errors in measurements or observations	Individual to population	Acknowledging, accounting and reporting uncertainty are required for a proper assessment of effects on fish responses. Uncertainty is also required for meta-analyses	Hierarchical models (maximum-likelihood or Bayesian approaches), simulation models	(Cressie, Calder, Clark, Ver Hoef, & Wikle, 2009)

Box 2

In the run-of-the-river Dunvegan hydroelectric project proposed for the Peace River in northern Alberta, Canada, all aspects of the originally proposed traditional hydroelectric station design were reconsidered when passage systems for both upstream and downstream fish movements were more thoroughly contemplated. Innovations included upstream fishways, which were developed through physical hydraulic modelling, starting with a random rock ramp (Katopodis, Shepherd, Johnson, & Kemp, 2004). Several downstream fishways or bypass channels were incorporated to allow different species to choose preferential movement paths, while at the same time using water, which would normally go over the spillway. Using this approach, spilling water could be directed where it would be most beneficial to guide and pass fish downstream, while at the same time, allowing flexibility to manage hydro station flow releases to maximize power generation. Field assessment of best flow conditions to attract or guide and pass upstream- or downstream-moving fish could be used to operate the power station, enabling adaptive management (Katopodis, Chilibeck, Kemp, & Johnson, 2007).

Furthermore, there is a need for a better evaluation of the ecological effects of fishways (Table 2), such as effects on the Darwinian fitness of fishes, impact of passage delay, energy depletion and physiological stress, fallback, carry-over effects, and altered population distribution (Burnett et al., 2014, 2017; Cooke & Hinch, 2013; Hinch & Bratty, 2000; Lucas et al., 2009; McLaughlin et al., 2013; Baumgartner, Boys, Stuart, & Zampatti, 2010; Williams, Zabel, Waples, Hutchings, & Connor, 2008). Lack of long-term and post-dam passage data sets on most species and river systems worldwide limits sound conclusions about fishway effectiveness (Bunt et al., 2016).

More research is needed on the selectivity of fishways for two main reasons. Firstly, for effective assemblage functionality, most fishways are too selective and greater effort is needed to aid species restoration plans (Cooke & Hinch, 2013; Foulds & Lucas, 2013). Secondly, and conversely, some river systems and fish communities are increasingly at threat from colonization by non-native invasive species or require ongoing management of such species. Here, there is a need for the effective development of highly selective fish passes able to prevent or strongly inhibit passage of non-native species (Rahel, 2013), while also allowing a high proportion of native species to pass (McLaughlin et al., 2013; Pratt et al., 2009). Of course, there is complementarity between these contrasting needs. For example, determining the mechanism responsible for extremely low ascent success for threatened European river lamprey (*Lampetra fluviatilis*, Petromyzontidae) (Foulds & Lucas, 2013) could have translational value for minimizing passage success for invasive sea lamprey (*Petromyzon marinus*, Petromyzontidae) in the North American Great Lakes. Extending the selectivity theme, there is an increasing trend, particularly with nature-like fishways, to regard these as biota migration corridors for a much wider range of species than just fish and this perspective needs greater research and development consideration (Louca, Ream, Findlay, Latham, & Lucas, 2014).

The observation that nature-like fishways tend to have low attraction efficiency but high passage efficiency, and the converse pattern for fishways of technical construction (see Bunt et al., 2016), provides opportunity to try and learn from the relative successes of different passage types. Site-specific conditions (e.g., gradient, lack of space) may limit the ability to install nature-like fishways at all facilities, but there are lessons that can be taken from the high passage efficiency at nature-like fishways to improve function of technical fishways. Explicitly contrasting the performance of different fish passage types using standardized/consistent methods would seem to be a fruitful and timely research topic.

4 | SHIFTING THE PARADIGM IN FISHWAY ENGINEERING

Behavioural rules which govern how fish respond to complex flow fields in estuaries, rivers, lakes and near various man-made structures, especially what attracts or guides them, are a high research priority. Attraction and fish guidance mechanisms for larger rivers and waterways are particularly challenging (Katopodis, 2005). More challenges arise in systems with a number of barriers and cumulative effects (Caudill et al., 2007) or in complex megadiverse systems with tropical species. Within fishways, research on flow fields which match the stimuli needed to cause fish to approach, enter and ascend a structure would help guide designers to examine the most feasible scenarios for maximum passage efficiency.

Understanding of the fine-scale relationships between turbulent hydraulic environments, sensory function, biomechanics, and individual and schooling animal behaviour in the air-entrained, turbulent and often turbid environments that characterize many fishways is crucial to elicit fish responses which improve attraction/approach entry and passage for multiple species (Keefer et al., 2011). More flexible computational fluid dynamics models, in-stream flow monitoring, new imaging techniques, 3D tracking of fish and/or fish-borne sensors of hydraulic conditions techniques are needed to solve this. Transfer of such knowledge from controlled experiments to field-based fish passage conditions would allow for better understanding and verification and thus has the potential to translate into increased effectiveness in practical applications. Controlled laboratory experiments (Haro, Odeh, Noreika, & Castro-Santos, 1998) that are run concurrently with field-based studies over several years (Arenas, Politano, Weber, & Timko, 2015; Goodwin, Nestler, Anderson, Weber, & Loucks, 2006) may be one of the best ways to fill these major knowledge gaps.

Knowledge of natural levels of migration success or failure, as well as the percentage of a fish population that needs to pass a barrier both ways to sustain a population, forms the basis for fish passage considerations and design to achieve suitable performance. It is generally recognized that to be effective, upstream or downstream fish passage systems need to perform the following functions with minimum delay: (i) offer hydraulic field guidance for fish to locate fishway entrances, either upstream or downstream ("Approach" phase, Equation 1); (ii) aid them to enter the fish passage system and transition into its actual passageway (both upstream and downstream) ("Entry" phase, Equation 1); (iii) provide hydraulic conditions that match the biological needs, abilities and behaviours of the species and life stages to facilitate passage ("Internal passage" phase, Equation 1). Furthermore, fish passage should maximize rates of passage through desired routes while minimizing the (a) rates at which those preferred routes are rejected; (b) rates and duration of exposure to undesired routes; and (c) post-dam passage impacts on behaviour, reproduction and survival.

Quantifying suitable hydraulic characteristics which can be translated into improved fishway designs to match biological needs has only been enabled by recent advances in fish tracking technology. Evaluations of fishways with various species has demonstrated quantitatively the significance for fish responses to complex hydraulic characteristics (velocity, turbulence, shear stress, circulation patterns, eddy size and streaming or plunging flow) (Cotel, Webb, & Tritico, 2006; Kemp, Gessel, & Williams, 2005; Liao, Beal, Lauder, & Triantafyllou, 2003; Lupandin, 2005; Marriner, Baki, Zhu, Cooke, & Katopodis, 2016; Silva, Katopodis, Santos, Ferreira, & Pinheiro, 2012; Thiem et al., 2013). Considering such findings, it seems that endeavouring to provide hydraulic energy dissipation to match fish swimming speeds with mean water velocities in fishways is rather simplistic and insufficient. Incorporating improved understanding of fish behaviour to fundamental fishway design aspects, such as attraction and guidance or passageway hydraulic characteristics, requires innovation and engineering paradigm shifts. For example, modifying or replacing conventional fishways to resemble natural channels—the nature-like concept—reproduces a diversity of natural hydraulic gradients more suitable as movement corridors for multiple species.

More broadly, flow management at dam facilities and the design of fishways may be dissected and rethought from a fish passage perspective, as much as from the perspective of other project goals. Devising and testing solutions informed by knowledge on species behaviour is promising research which may lead to more advanced and effective engineering applications (Burnett et al., 2017). Advances through scientific research, translated into practical design changes on existing facilities, have already produced promising results. For example, modifications to Kaplan turbines have achieved high survival for migrating juvenile Pacific salmon (Cada, Loar, Garrison, Fisher, & Neitzel, 2006; EPRI-DOE 2011). Better yet, new hydroelectric turbines, inspired by the ancient helical Archimedes pump, have already undergone significant testing with encouraging results for many species, including sizable adult American eel (*Anguilla rostrata*, Anguillidae) and white sturgeon (*Acipenser transmontanus*, Acipenseridae) (EPRI-DOE 2011). Substantial research has been performed on developing a fish-friendly turbine (The Alden turbine) (Dixon & Hogan, 2015). Although this new technology holds promise to become an advanced and effective engineering application for fish downstream migration, it has yet to be demonstrated in a field application.

Increased discharge over spillways or through special surface bypasses can provide safe routes for downstream migrating salmon (Adams, Plumb, Perry, & Rondorf, 2014; Fjeldstad et al., 2012). Redesigning traditional spillways or parts of them from vertical to angled orientations may offer improved downstream passage of European eel and possibly other fish species (Silva, Katopodis, Tachie, Santos, & Ferreira, 2016). In a rare example of successful fishway design from biological principles, Haro et al. (1998) showed that passage of juvenile Atlantic salmon (*Salmo salar*, Salmonidae) and American shad (*Alosa sapidissima*, Clupeidae) can be dramatically improved at downstream bypass weirs by reducing the rate of acceleration of flow as it passed over the weir. This was achieved by replacing a sharp crest with a graduated bell mouth, the idea being that the velocity gradient experienced by fish is proportional to their body size, and by stretching this out, the gradient could be reduced to a level below that which elicited a startle or avoidance response. This concept has been broadly applied to dams on both coasts of North America. The underlying biological basis has been repeated for other species (Enders, Gessel, & Williams, 2009) and has resulted in dramatic reductions in the amount of spill required to safely pass downstream migrants (Adams et al., 2014). The success of this technology is credited with meeting management requirements for protection of endangered species, while simultaneously permitting improved hydroelectric generation (Adams et al., 2014).

Innovative thinking and engineering design focused on the needs of multiple freshwater fish species of a wide range of sizes, as well as power generation, are realistic and are starting to be implemented (see Box 2 for example of the run-of-the-river Dunvegan hydroelectric project proposed for the Peace River in northern Alberta, Canada).

5 | OVERCOMING BARRIERS THAT LIMIT OUR ABILITY TO IMPLEMENT EFFECTIVE FISH PASSAGE SOLUTIONS

Many countries have developed specific legislation and policy with the aim of protecting migratory fish. Legislation generally requires that developers must provide fish passage at any new structure, or existing structures that are substantially modified. The absence of adequate legislative protection can be a substantial barrier to implement effective solutions, although in some cases, legislative direction to provide fish passage is probably less effective than incorporating other conservation options, such as preventing damming on key tributaries as proposed in some large tropical river systems (Pelicice et al., 2015). Equally significant is policy compliance and a review process to ensure that solutions genuinely provide adequate protection for migrants. Moreover, in many regions, especially in tropical countries, there may be insufficient legislation or funding to ensure adequate basic studies related to fishways, as well as for their implementation and robust monitoring effectiveness (Kemp, 2016). When funding support is available, it is frequently related to the licensing process of a particular hydroelectric project to be implemented, with limits regarding, for instance, the available time for pre-dam condition studies. In Brazil, however, specific legislation has enabled the support of the majority of the fish passage-related research. Public distribution, electrical energy transmission and production service concessionaires are required to annually invest a minimum of 0.4% of their net operating income in technological research and development projects in the electrical energy sector. Because the total budgets are high, this small proportion translates into substantial budgets for fish passage research and development. Another tactic to take is to include in the power rate paid by consumers the cost of actions to mitigate for environmental damage that results from hydropower dam construction and operation. This is the case with hydropower regulation in the United States (McFarland, 1966); moreover, a special situation occurs in the Pacific Northwest of the United States for hydropower produced in the Columbia River Basin. *The Pacific Northwest Electric Power Planning and Conservation Act, 1980*, met two regional goals: (i) provide efficient and reliable power and (ii) restore anadromous fish resources damaged by development of the hydroelectric energy supplies (Williams & Tuttle, 1992). As a result of this act, the cost of electricity produced by hydropower dams includes all costs (research, operations, and management oversight) associated with fish passage issues at dams and restoration of habit to mitigate for hydropower losses. In 2015, the Fish and Wildlife Program costs were estimated at US$757 million (Northwest Power and Conservation Council 2016).

Ensuring that an appropriate solution will be developed largely depends on the success criteria set by the project team. Generally, the ability of a fishway to meet the performance targets (see Section “The Missing Pieces: Knowledge and Tool Needs”) is dependent on several factors. First, the overall size of the barrier: larger barriers often require more complex fish passage solutions. Second, identifying target species is critical. Designers need to determine whether the required solution must pass an entire fish community, some subcomponent of species, or a smaller number of any target fish species. Thirdly, the local hydrology needs to be understood to ensure that fish passage solutions function over the entire flow range. Finally, the fourth consideration is cost. Different solutions may have different costs, with varying expectations of fish passage efficiency and long-term effects on fish populations. Project teams need to lay out the range of possibilities and point out the full range of ecosystem service consequences for the various project options both immediate and long term (e.g., to allow/promote recreational fishery and the ecological services that some species can promote such as the transport of nutrients upstream) so that decision-makers understand the possible outcomes of choosing different passage solutions, particularly as available budgets often limit most fish passage solutions. Decision-makers need to recognize that the ability to achieve a holistic solution may not be possible without the ability to make a substantial investment to achieve some predetermined outcome.

Where fishways are installed at dams that have impacted fish populations and fisheries, consideration should be given to setting overall targets for fisheries recovery during that process. For new dams, incorporating fishways and targets for outcomes (e.g., no net change in fisheries productivity) should be but are often not applied. Any benefit arising from improved fish passage should be measured against these targets. In many instances, historical population levels remain unknown and thus it is difficult to set a pre-construction benchmark (Cooke & Hinch, 2013). In these cases, surrogate targets could be set, which can include the timing of passage, the number of species or individuals passing, and quantitative metrics such as attraction and passage efficiency of the structure. Other targets such as the size composition of the assemblage using the pass or numbers of species passing through, compared to those upstream and/or downstream, can be less satisfactory in terms of demonstrating passage performance, but sometimes may be all that is feasible, especially in large rivers with high fish diversity (Oldani, Baigún, Nestler, & Goodwin, 2007). This will allow identification of possible artificial selective pressure imposed by the fishway. Recent research suggests that behaviour type (i.e., where individual fish sit on the shy-bold continuum) has little influence on fish passage success (Landsman, Wilson, Cooke, & van den Heuvel, 2017), but more work on that topic is needed on a broader suite of fish species. Understanding the consequences of reduced passage or increased passage delays on a species-by-species basis or an entire life cycle of a species represents a critical but poorly understood component of population management (Burnett et al., 2014; Caudill et al., 2007; Roscoe, Hinch, Cooke, & Patterson, 2011). The implications of not developing a strong approach to measure success can represent a barrier for future works. We surmise that the failure of a previous fish passage project may be used as justification not to proceed with any solution at all; however, we failed to find documented examples of this in the peer-reviewed literature.

Once restoration targets and species have been defined, consideration should also be given to the value of the habitat being reconnected; this can also be a major problem in implementing fishways as general solutions. For example, Pelicice and Agostinho (2008) reported case studies from Brazil where fishways were acting as “ecological traps” and were potentially contributing to population decline rather than recovery. Such a condition occurs when “the environment above the passage has poor conditions (e.g., the absence of spawning grounds and nursery areas), and the environment below the passage has a proper structure for recruitment, and is particularly harmful when a big reservoir is created,” hindering the possibility of downstream passage (Pelicice et al., 2015). International fishway success was used as legally enforced justification to develop local fishway solutions; however, there was little consideration to local species biology and ecology. Fish successfully ascended the fishways but were then exposed to suboptimal habitats which led to spawning failure. Similar knowledge gaps exist for understanding the basic biological requirements of many species worldwide, especially in megadiverse tropical rivers. For example, Baumgartner et al. (2012) reported capture of 73 species during targeted fishway design research on the Mekong River in Laos, including a number of undescribed species for which limited biological knowledge exists. Effective fish passage for entire fish communities, rather than target species, is challenging and is a major barrier to progress.

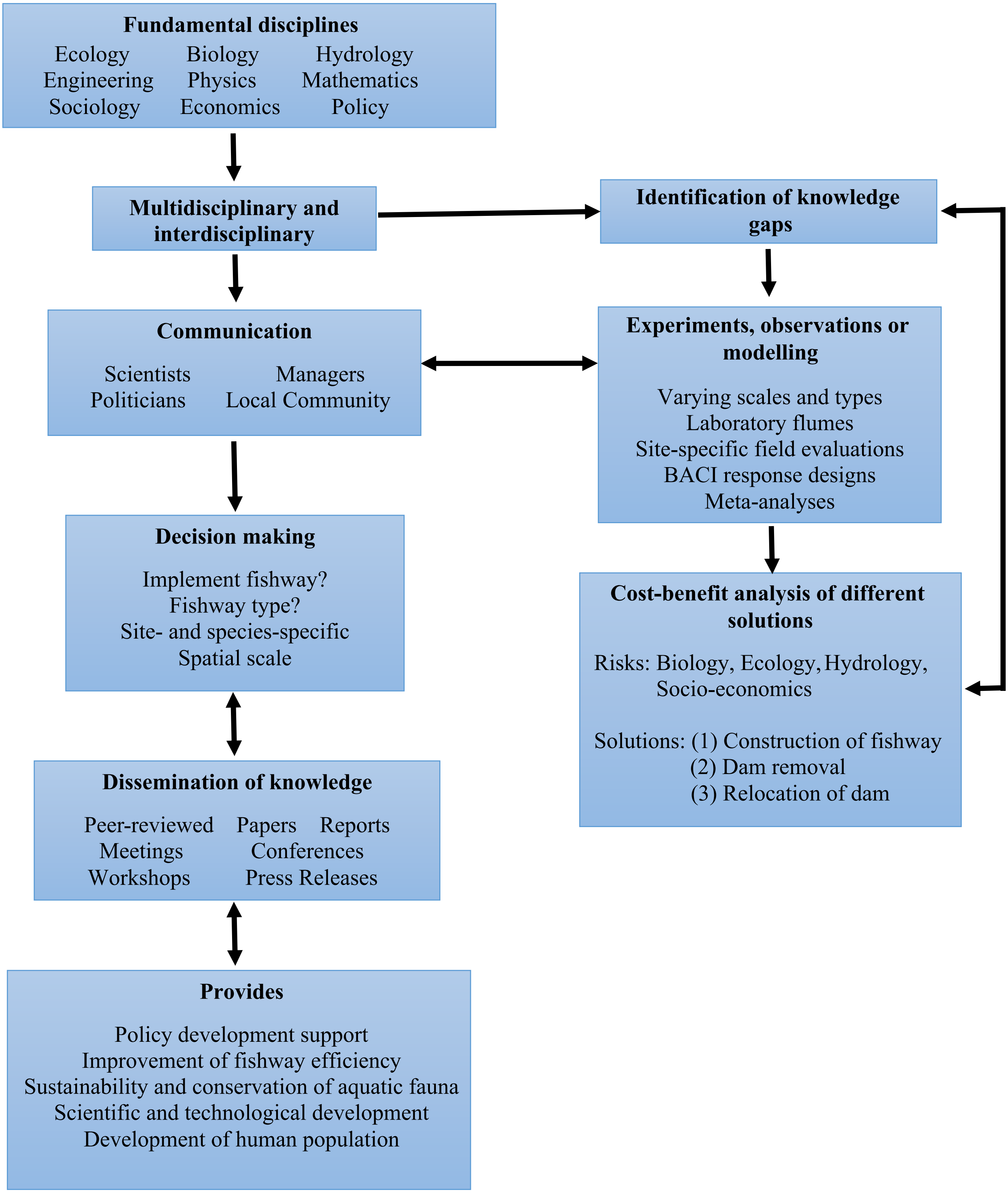

FIGURE 2 Conceptual framework of the fishway science process [Colour figure can be viewed at wileyonlinelibrary.com]

While substantial knowledge gaps may be limiting our ability to design and implement effective fish passage solutions, there are endless opportunities to learn from existing structures. Both Bunt et al. (2016) and Noonan et al. (2012) highlight the paucity of published information on quantitative measures of fishway success, assessed using metrics such as attraction and passage efficiency. For example, Hatry et al. (2013) identified 211 constructed (i.e., more than a simple culvert) fishways across Canada, and only 9% of these were subject to rigorous biological effectiveness evaluations. Indeed, this highlights that construction of a fish passage facility is a single step in a multistep process. If investment is not made into detailed and iterative monitoring, future projects will be disadvantaged by not being able to learn from existing works. Investment in ecological knowledge, not just capital infrastructure, is crucial and needs to be integrated into national and international development planning.

We highlight the urgent global need for biologists, engineers and developers to make use of existing information and also forecast knowledge needs in the context of future opportunities. By 2050, it has been estimated that the world will require 70% more agricultural production, and by 2035, 50% more primary energy (Bruinsma, 2009; de Fraiture et al., 2007). To meet these demands, irrigated agriculture will need to be extended (Döll, 2002) and small hydropower development will require continued rapid expansion (presently expanding at 1500% per annum; Zarfl et al., 2014). Consequently, there will be increased conflict over limited resources unless appropriate steps are taken to improve efficiencies on a global scale. Globally, the main challenge is to balance social, economic and ecological benefits, across critical thresholds, in order to meet long-term development objectives (Grigg, 2008). Fish passage and habitat needs must be a critical consideration in that process.

6 | TRANSLATION OF FISH PASSAGE EXPERTISE AND INFRASTRUCTURE BETWEEN AND WITHIN GEOGRAPHICAL REGIONS

Extension of fish passage ideas, designs and concepts has been a cornerstone of international collaboration for many decades. Many years of targeted fish passage research in North America, Australia and Europe have advanced fish passage construction elsewhere. For example, the hydropower project at Bonneville Dam (Columbia River, USA) has acted as a template for many similar projects in other countries. Concepts developed at Bonneville Dam have been directly applied to projects in Brazil and South-East Asia (Baumann & Stevanella, 2012). Further, the design of the Ben Anderson Barrage fishway (Burnett River, Queensland) was directly applied at Stung Chinit Irrigation district in Cambodia (Baumgartner et al., 2012). It is clear from these examples that, in the absence of suitable local solutions, there is a strong trend to adopt and apply existing solutions from elsewhere.

However, the concept that migration routes for fish can be universally reinstated through the installation of fishways resulting from the transfer of expertise and infrastructure between and within geographical regions has generated substantial debate (Kemp, 2016). Some successes have been reported (Barrett & Mallen-Cooper, 2006; Baumgartner, Zampatti, Jones, Stuart, & Mallen-Cooper, 2014; Parsley et al., 2007), especially at sites where solutions were specifically developed to meet target species and hydrology. But the precarious conservation status of native population reduction of migratory species in South America (Agostinho, Gomes, Fernandes, & Suzuki, 2002; Agostinho, Gomes, & Latini, 2004), and the disrupted river connectivity throughout Africa (Jewitt, Goodman, Erasmus, O'Connor, & Witkowski, 2015; Nel et al., 2007; Wasserman, Weyl, & Strydom, 2011) and Asia (Dudgeon, 2005), clearly indicates that these strategies cannot be applied everywhere. Understanding the reason of this failure is critical, as the world's most biodiverse river basins (the Amazon, Congo, and Mekong) are experiencing an unprecedented boom in construction of hydropower dams (Winemiller et al., 2016), and their effects on biodiversity and fisheries are potentially enormous.

After relying on international designs that were largely ineffective, some countries went through a fishway design phase in the early 2000s where the importance of region-specific fishways based on the local species was incorporated (Barrett & Mallen-Cooper, 2006). Recognizing that different species have contrasting passage requirements was a significant first step which was required to shift expectations from single species to entire fish communities (Baumgartner, Boys, Stuart, & Zampatti, 2010; Baumgartner et al., 2012).

Guidelines for local fishways are now available for some regions (Bok, Rooseboom, & Rossouw, 2004), but they are far from mitigating the effect of the physical and chemical barriers. Part of the problem is related to the life-cycle differences between the tropical and temperate migratory fish fauna, and the lack of a broader view of the river basin system, without considering the maintenance of long enough free-flowing rivers and critical habitats (Pompeu et al., 2012). Moreover, reservoirs are often acting as an ecological barrier to downstream movements (Jepsen et al., 1998), and even more so in the larger tropical reservoirs (Pelicice et al., 2015). Smaller barriers in temperate streams rarely cater to downstream migrants, despite being known to contribute to large mortality rates (Aarestrup & Koed, 2003; Baumgartner, Reynoldson, & Gilligan, 2006).

In this scenario, the translation of fish passage expertise and specific infrastructure seems to be limited in providing real solutions. In such instances, collaboration within the international community is crucial for sharing unique designs and especially associated successes and failures in the different monitoring approaches. Capacity building related to the science, engineering and practice of fish passage is needed (Franks, 1999). Notably, this is particularly evident in parts of South America, Africa and Asia where there is still an urgent need for training, dissemination of information and technology in regions of in-house expertise through mechanisms such as the KEEPFISH project hosted in Chile, in cooperation with European partners. Despite the opportunities and formal processes, reinstatement of fish passage is unfortunately the exception rather than the rule. For example, 10% of large dams in the United States have bidirectional fish passage (Fausch et al., 2002) and <3% of dams in Australia have fishways (Harris, Kingsford, Peirson, & Baumgartner, 2016). So, even in instances where foundational research has been performed and a suitable design implemented, the lack of a robust and ongoing monitoring programme often precludes an effective determination of whether the implemented solution has achieved its goal of rehabilitating local fish communities. Such an approach is critical to underpin effective dissemination of fish passage technology to other sites and locations.

7 | FROM SCIENCE TO ACTION

In most jurisdictions, regional or Federal management agencies serve as the regulator as it relates to the installation of dams on riverine systems. Various policies and regulations dictate when and whether fish passage is needed. Often the regulator will provide direction on key fisheries management and conservation targets or other parameters that would guide passage options. The project proponent (often a hydropower utility in the case of larger dams) and their staff or contractors (e.g., environmental consultants, design engineers) would then develop a series of options that consider technical feasibility, cost and ability to achieve the fisheries management and conservation objectives. Ideally, the entire process is supported by a rich and credible evidence base to ensure that the decisions made are most likely to achieve the desired management objectives or targets (Figure 2). In principle, this process sounds rather straightforward but rarely is it so linear or simple. For example, consider a scenario where the governance structures are weak (or non-existent) and the regulatory agency lacks the scientific or engineering capacity to advise or make informed decisions regarding fish passage. While this is most likely an issue in developing countries, internal science and engineering capacity specific to fish passage in developed nations is absent in many jurisdictions such that decisions may be left to those without any specific training or expertise related to fish passage. Beyond stating the obvious need for addressing those issues, solving them is beyond the scope of this review. However, there are still a number of challenges that can and do exist related to moving from science to action in jurisdictions with well-developed and defined governance structures and reasonable science capacity.

The idea that science should underpin decisions in natural resource management is one that we suggest to be embraced by any rational person. Yet, science is imperfect and it is easy to "cherry pick" results or studies from the literature while ignoring others (i.e., creating bias). Of course, this assumes that a decision-maker has access to the necessary library resources—often which hide behind paywalls. There is also an assumption that just because something is "peer-reviewed" that the science is strong. We know that is not always the case. Even when scientific information is available, it is well known that environmental managers often rely on their past experiences or input from their colleagues to guide them (Pullin, Knight, Stone, & Charman, 2004), and more broadly we suffer from confirmation bias. In the late 2000s, a number of scholars began to call for what is described as an "evidence-based" approach to conservation and natural resources management (Sutherland, Pullin, Dolman, & Knight, 2004). Following the approaches used in the medical and health-care realms (Pullin & Knight, 2001), the authors called upon adopting evidence synthesis techniques known as systematic reviews to guide decision-making (Pullin & Knight, 2009). Systematic reviews are highly repeatable, and rigorous evidence synthesis methods ensure management decisions are based on the most defensible information (Pullin & Stewart, 2006). Findings from studies with poor experimental design are omitted, and answers to well-defined questions are addressed with strong certainty assuming a reasonable evidence base exists (Pullin & Stewart, 2006).

To date, there has been only one attempt to conduct systematic review related to fish passage, although we do recognize several key meta-analyses on fishway functionality (Bunt et al., 2012, 2016; Kemp, 2016; Noonan et al., 2012). Bunt et al. (2012, 2016) included relatively few studies in their analysis as many of the existing studies failed to meet basic criteria for inclusion in their meta-analysis (exactly what one does in systematic reviews); this emphasizes the need for the scientific community to do a better job with research and monitoring. Today, we presume that the literature base remains fractured and variable such that the same problem persists—hopefully this review (and see Castro-Santos & Haro, 2010; and Cooke & Hinch, 2013) will help to guide researchers so that systematic reviews will be possible in the near future.

It is also conceivable for fish passage research to fail to address questions that are relevant to managers, essentially driving them to base decisions on their experience rather than formal scientific study. For example, most developers and managers overlook the potential for sublethal costs of fish passage. So, what if cortisol or excess post-exercise oxygen consumption (EPOC; Lee, Farrell, Lotto, Hinch, & Healey, 2003; Burnett et al., 2014) is elevated after passage? If that elevation in cortisol or EPOC is linked to migration or reproductive failure, that issue is suddenly relevant to managers. Knowledge of the consequences of repeated passage attempts, migration delay, energy depletion, fallback, chronic stress from non-passage and delayed passage on the reproductive ecology and fitness of individual fishes scaled to the population level (Burnett et al., 2014, 2017) (e.g., effects such as increased probability of mortality from physiological failure, from increased predation risk; reduced probability of arriving at suitable habitat e.g., spawning grounds; resorption of gonads; reduced growth potential) is relevant to managers but needs to be framed around fish passage issues. This requires gathering long-term data sets of the outcomes for fish that do not pass, or that pass under potentially compromised circumstances, and comparing them to control conditions (Bunt et al., 2012; McLaughlin et al., 2013).

From a fisheries management perspective, specific information on attraction and passage efficiency and overall survival following dam passage will be relevant information. However, this is only part of the puzzle. What is really needed is an understanding of the necessary performance of a fishway for a given species to maintain a fish population to a desired level. Ecologically relevant results require determining specific hydraulic requirements or constraints that fish need or avoid when migrating and dispersing. Engineers cannot develop effective fishways without those hydraulic data, but that does not mean that such information will guarantee that a fishway will work. Past experience has shown that it is not a straightforward process. Iterative testing and monitoring is required before a final configuration is determined that will effectively pass the species and life stages of interest. Moreover, researchers and managers rarely consider whether the fishery (or fisheries management objectives) will change in the future (and hence design needs change) or whether the operation of the structure may change in the future (and hence push the fishway outside operational limits). In other words, the fishway needed today may not be the fishway needed tomorrow. It is also necessary to de-emphasize fish passage as the sole solution to the long-term maintenance of migratory fish populations and facilitating dispersal at key life stages. This approach recognizes that fish passage is one part of the solution but also depends on the maintenance of critical habitats, the reduction of the mortality in different life-cycle phases, fisheries control, etc.

The science and engineering behind fish passage can be described as mission-oriented but also depends on more theoretical studies and knowledge. The key is to do science that is relevant to managers (see Chapman et al., 2015 on tips for "being relevant") and ensure that when the research is completed, it is communicated in an effective and useful manner. Simply handing a peer-reviewed empirical study to a practitioner is unlikely to be effective, as knowledge has been shown to move in more complex ways—that is not in a linear fashion from researcher to manager (termed "pipeline model," van Kerkhoff & Lebel, 2006). Greater dialogue is needed between the practitioners and researchers to determine the types of user-friendly products that would be of assistance to those tasked with making decisions. Such products could be extensions of the aforementioned systematic reviews. Moreover, there is a need for mechanisms to enable regular updates as additional information and guidance becomes available in this dynamic field. Again, systematic reviews provide opportunities to regularly update the evidence base. There are many opportunities to improve the science-action interface (Cook, Mascia, Schwartz, Possingham, & Fuller, 2013) to ensure that the right information finds its way into the hands of practitioners in a timely manner. Research on how practitioners engaged in fish passage obtain knowledge on fish passage science and engineering as well as their preferred methods of receiving such information could further inform knowledge mobilization and exchange activities.

8 | CONCLUSION

The wide range of skills relevant to fish passage issues means that if we are to be effective in our goal of greatly enhancing river connectivity for fishes, we need to embrace and employ the full range of relevant disciplines. More specifically, we need to better integrate the use of these skills through interdisciplinarity and recognize that solutions for a specific site, in a specific country, may not apply elsewhere. Collaborative approaches are vital, and centres of excellence combining a broad range of expertise and capabilities would be beneficial.

Acknowledging the trade-offs between environmental and water resources (Rodríguez et al., 2006), as well as the balance between fish passage and other mitigation strategies, is crucial to the development of future research on fish passage. There is a need to identify instances in which fish passage is beneficial or not to ecosystem integrity and population biology of fish species, and integrate this knowledge in decision-making (e.g., in many cases, river restoration may imply barrier removal). Overall passage effectiveness needs to be placed in the broader context of population biology (e.g., behaviour, reproductive biology, genetics and population dynamics) and access to good-quality habitat to be meaningful and consequential.

It is critical to formulate a standardized approach to assessing fish passage that provides long-term ecologically relevant and meaningful results over time and across regions, as well as documenting cases and identifying situations in which fishways contribute to the conservation of migratory species. Innovative monitoring approaches that push the boundaries of technology to provide cost-effective and accurate data are also essential. Moreover, fish passage research will benefit by including studies of cumulative effects that consider and quantify the effect of pre-barrier experience on barrier passage and post-barrier passage success (Burnett et al., 2014). Likewise adaptive management will be facilitated if long-term continuous monitoring programmes are consistently employed (Birnie-Gauvin, Tummer, Lucas, & Aarestrup, 2017).

More effective and open access ways of sharing information and knowledge across the development and management communities research (such as Movebank, FishBase, CanFishPass, Swimway South Africa) about information pertinent to river biodiversity conservation, impacts of dams on fish and fisheries, fish passage performance and design, dam removal, methods and technical standards are needed to improve the quality of information on which to base decisions. In this context, adaptive management is essential. We need to learn from designs that have failed, develop suitable solutions and test these solutions at new sites. The cumulative benefits of adaptive management are essential for the long-term advancement of fish passage science. Ultimately, this will improve biodiversity sustainability as well as the support and development of human population.

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CONFLICT OF INTERESTS

Most co-authors have had funding from industry partners related to fish passage science.

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