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Review

Developing performance standards in fish passage: Integrating ecology, engineering and socio-economics

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ABSTRACT

The construction of dams and weirs has fragmented many rivers and streams globally, and this is a major threat to biodiversity. The most common method used to reduce these impacts is to construct fishways. Published examples show that while fishways can be effective, their performance can also be highly variable. Given this variability, it is critical that transparent targets are set and criteria are developed to assess fishway performance. Often though, this is not done, leading to uncertainty about what constitutes acceptable fishway performance. We present a conceptual framework that illustrates how fishway performance standards sit within a wider process involving objective setting, fishway design, and assessment, and then outline the key principles in the development of fishway performance standards. We highlight the importance of setting clear ecological objectives based on a 'guiding image' (the desired characteristics of the fish assemblage above and below a barrier), and fish passage objectives (i.e. required proportion of the fish assemblages, either individual species or life stages, that needs to be passed without delay and over an expected range of flows). We describe the biological and hydraulic characteristics that need to be considered in performance standards, and highlight the relevance of these characteristics to fish attraction, passage and exit. We use four case studies from diverse riverine systems to provide examples of how performance standards have been set and progress towards their assessment. We conclude by highlighting the potential benefits and risk of using performance standards and identifying areas of uncertainty for future research. Keywords: ecological objective, fishway, fish migration, fishway efficiency, performance metric, rehabilitation.

1. Introduction

River regulation and the associated construction of infrastructure such as dams and weirs, has substantially fragmented aquatic landscapes, causing declines in global biodiversity (Dudgeon et al., 2006; Dugan et al., 2010; Grill et al., 2019). Riverine fish are a highly affected group (Deinet et al., 2020) which is of particular concern given that riverine fish provide many ecosystem services including cultural (e.g., ceremony) and provisioning (e.g., nutrition, livelihoods) services that directly benefit humans (Lynch et al., 2016). One of the most common methods used to reduce these impacts is to provide fish passage via fishways, which perform an important role in maintaining stream continuity and improving connectivity (Jungwirth, 1998; Mallen-Cooper, 1999; Northcote, 1998; Silva et al., 2018). Fishways come in many forms ranging from engineered structures manufactured almost entirely of concrete to more nature like designs that look like real fluvial systems (reviewed in Clay, 1995). The global interest in fishway construction has often been driven by attempts to maintain migratory fish stocks and fish communities by reducing the impacts of disruptions to longitudinal movement (e.g. Baumgartner et al., 2012; Bunt et al., 2012; Godinho and Kynard, 2009; Silva et al., 2018).

The high-level objectives of fish passage are clear – to improve or maintain multi-species fish populations – but most attention is given to the biological and hydraulic aspects of fishway design needed to achieve fish passage (e.g. Baras and Lucas, 2001; Clay, 1995; Larinier et al., 2002). Some fishways have directly restored the diversity and abundance of upstream fish communities (e.g. Hodge et al., 2017; Marques et al., 2018; Rourke et al., 2019) and occasionally other aquatic taxa,

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such as freshwater mussels (e.g. Benson et al., 2018) and invertebrates (e.g. Rawer-Jost et al., 1998; Stuart et al., 2008a, 2008b). However, fish passage rates are almost always highly variable, and can range from 0 to 100% (reviewed in Bunt et al., 2012; Birnie-Gauvin et al., 2019; Hershey, 2021; Roscoe and Hinch, 2010). This variability has led to uncertainty about what constitutes acceptable passage and fishway performance (Cooke and Hinch, 2013; Silva et al., 2018), especially because fishway performance targets and recommended performance criteria are not commonly articulated (Silva et al., 2018). Even the most contemporary (2019–2021) fishway assessments almost universally lack explicit 'a priori' biological and hydraulic performance standards from which to set 'a posteriori' evaluation targets (Box 1).

When field assessments of fishway performance are undertaken, there is often not a transparent link back to the fishway design objectives (although there are exceptions e.g. Mallen-Cooper, 1994, 1999), and so success or failure is difficult to objectively define. Evaluations also often focus on passage at the site scale, and yet fish passage objectives are likely to be spread across different spatial (fishway, dam site, river system), and temporal (hour, day, season, single generation, multiple generation) scales. These are also three different groups in a fishway project: (i) users of the ecosystem services, who have specific objectives, (ii) fishway designers (fisheries engineers, fish biologists), who need to balance cost versus function and objectives, and (iii) scientists assessing fish passage, who may or may not have been involved in fishway design. The separation of these groups leads to further disconnection of objectives and evaluation.

The objective of this manuscript is to provide a framework that clarifies these linkages, integrating the spatio-temporal scales of a fish passage project with the different disciplines and groups involved, to enable the development of appropriate performance standards. We present a conceptual framework that illustrates where performance standards sit within a wider process of fishway objective setting, design and assessment. We highlight the importance of initially setting clear ecological and socio-economic objectives and show how these link to fish passage objectives and design criteria. We then clarify the links to performance standards, and highlight the relevance of these to fish attraction, passage, and exit. We examine this framework using four global case studies of fishways from diverse systems: (i) a high-discharge, tropical South American river (Parana River, Brazil), (ii) a high discharge, tropical Asian river (Mekong River, Lao PDR), (iii) a low-discharge, southern temperate river (Yarra River, Australia), and (iv) moderate-discharge temperate North American river (Seton River, British Columbia, Canada).

These case studies provide examples of how performance standards have been set, and progress towards these then evaluated. Our focus is on performance standards in relation to upstream movement of fishes, but we acknowledge that standards are also needed for downstream passage, and the same broad principles will apply. We discuss some of the potential benefits and risks of using performance standards, and important areas for future research. While every fishway is unique (e.g. due to local species with varying population dynamics, local hydrology and site-specific layout), the general principles we outline can be adapted and applied to a wide range of river systems to provide clarity to fishway designers, owners, stakeholders and rights holders.

It is important to acknowledge that there is a long history of examining fishway performance, and how this has done has changed through time. Up until the 1990s, the most common method to understand fish passage efficiency was to trap the upstream exit of fishways (Bunt et al., 2012; Silva et al., 2018). Although exit trapping did not provide an estimate of attraction or passage efficiency, over multiple years it provided an estimate of population change of some species (Mallen-Cooper and Brand, 2007). In the 1990s entrance trapping was used, with reduced velocity and turbulence, to obtain a sample of migratory fish that could locate and enter the fishway but potentially not ascend (e.g. Mallen-Cooper, 1999). Over the last 30 years, there has been expanding use of electronic tagging of fish and other methods to investigate attraction and passage efficiency. The learnings from these studies have been synthesised by four major review papers (Cooke and Hinch, 2013; Hershey, 2021; Noonan et al., 2012; Roscoe and Hinch, 2010). The reviews evaluate hypotheses, scientific methods and consistency of evaluation; examining the metrics used, their suitability and accuracy. These reviews did not directly address performance standards, although Noonan et al. (2012) and Cooke and Hinch (2013) note that broader population processes need to be considered in addition to fishway efficiency, and both quote the recommendation of Baras and Lucas (2001) of 90–100% passage as a standard. This paper differs from these earlier reports in that it focuses exclusively on the development and use of performance standards, and by integrating the links between project objectives, fishway design and fishway evaluation.

2. Background

2.1. Defining design criteria, performance indicators and standards

It is important to distinguish between design criteria, performance indicators, and performance standards to avoid conflating fishway objectives and the metrics that are used to measure performance. By *design criteria*, we are referring to specific elements of the fishway civil (physical) or hydraulic design such as pool size or turbulence. Biological knowledge about the local species (e.g. sizes, seasonality, diel patterns of

Box 1

We conducted a systematic literature review to examine how frequently fishway performance standards have been set in previous studies. The purpose of this review was to provide a snapshot of recent case studies from 2019-onwards.

We searched the Web of Science dataset using the term: ("fish passage" OR "fish bypass" OR "fishpass" OR "fishway" OR "dam passage" OR "fish ladder") AND ("assessment" OR "evaluation" OR "efficiency" OR "success" OR "rate"). This search term was used in a recent meta-analysis of fishway performance (Hershey, 2021), except that we also added "fish ladder" and "assessment". This returned 218 results in total from 2019 to 2022. We refined this list by including only quantitative studies (removing reviews and summaries of project-level outcomes), and eventually included 34 studies in our review.

For each study, we recorded if each paper measured performance indicators (the metrics or variables used to measure performance) or set performance standards before (a priori*)* or after (a posteriori) design and construction. Our definition of performance standard follows the definition in the main text i.e. the value of a metric that is needed to meet ecological, population, or socio-economic objectives. Each paper was scored in terms of considering biological and hydraulic metrics and standards.

We found that 97% and 44% of papers measured biological and hydraulic performance indicators. However, the percentage of papers that set performance standards was significantly lower: 8% and 15% set either a priori or a posteriori biological standards, 15% and 5% set a priori or a posteriori hydraulic standards, respectively. These results illustrate that while many recent studies are measuring fishway performance using biological and hydraulic indicators, very few are relating these measures to performance standards.

migration, range of flow conditions when fish migrate) informs the *design criteria*, as well as operating requirements. *Performance indicators* describe the metrics or variables used to measure performance while *performance standards* describe the actual value of the metric that is needed to meet ecological, population or socio-economic objectives. For example, fishway pool width and length are *design criteria*; these can be checked during construction for quality control, but they are not *performance indicators*. The percentage of fish finding the entrance of a fishway is a *performance indicator*, while 90% would be a *performance standard* if meeting this value means a fishway also meets ecological objectives. Another example is the maximum water velocity between fishway pools: this is a hydraulic *design criterion* used to calculate hydraulic head loss that determines step height between pools, which becomes a physical *design criterion*. Head loss (or maximum water velocity) is often also a *performance indicator* and, with a specific value and tolerance (i.e. 0.10 m +/− 0.01 m), becomes a *performance standard.*

Performance standards in fishways are used for two primary purposes: i) wet commissioning (first test of a new fishway with water) and regular inspections for operation and maintenance (O&M) – these largely use hydraulic metrics; and ii) biological evaluation, which can be passage at a fishway, through a site or broader population metrics. Without performance standards the specific objectives of a fishway and whether they have been achieved remains opaque.

3. A framework for fishway performance standards

3.1. Integrating fishway design and evaluation

There are many technical guidelines on fishway design that discuss design criteria, and contemporary examples provide the conceptual basis for providing fish passage and discuss high-level ecological objectives (e.g. FAO/DVWK, 2002; Franklin et al., 2018; O'Connor et al., 2017; Porcher and Travade, 2002). These serve as a good basis for exploring the development of fishway performance standards.

We present a conceptual framework (Fig. 1) that integrates the various components involved in setting objectives for fishways; show how these objectives should guide fishway design, and the development of performance standards that can be used for evaluation. We recognise that there are three spatial scales that need to be considered in this framework: the individual fishway, the site where a fishway is located, and the broader riverscape.

3.2. Socio-economic objectives

The key starting points for setting fishway performance standards are outlining clear ecological and/or socio-economic objectives (Fig. 1), which occur at the catchment or riverscape scale. Socio-economic objectives for fishways - particularly the maintenance of salmon fisheries - were the original reasons for early fishways (Katopodis and Williams, 2012). They remain key in developing nations, while maintaining biodiversity and ecosystem integrity have become contemporary objectives for fishways in developed nations (Baumgartner et al., 2021a; Cooper et al., 2019; Millar et al., 2019). Recreational fishing can be another set of socio-economic objectives; although rarely articulated as performance standards, they could form the basis of highly-measurable and applied metrics. Socio-economic objectives can directly inform fishway performance standards by using riverscape metrics of fisheries and food security.

Another important suite of socio-economic objectives that are often overlooked are Indigenous values. For example, in Australia, Indigenous

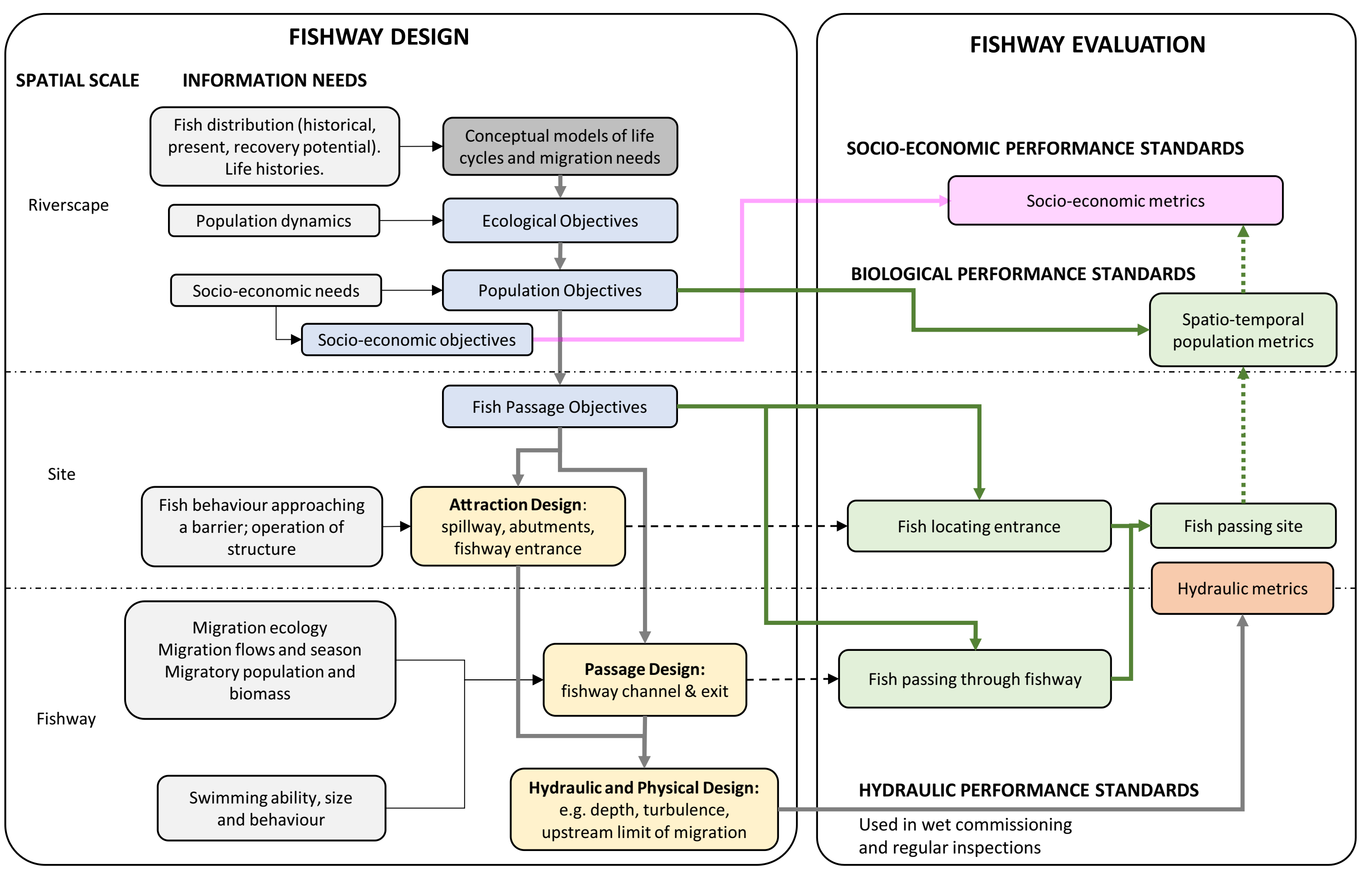

Fig. 1. Steps and information needs involved in setting fishway performance standards. Grey boxes are information needs, blue boxes are objectives, light orange boxes are engineering design; these lead to socio-economic (pink), biological (green) and hydraulic (orange) metrics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

peoples have an ongoing connection to land, water and aquatic biota for over 40,000 years and many fish have high totemic value (Balme and Hope, 1990; Gunther, 1926; Humphries, 2007). Knowledge of the seasonal migrations of fish has been exploited by Indigenous fishers to support riparian societies (Mathews, 1903).

3.3. Ecological objectives

Ecological objectives – such as restoration of a species or maintenance of fish populations after a new dam is built – often form the initial impetus for a fishway project. Nevertheless, they are often not articulated (or published in accessible literature), while the following step of setting specific population objectives is rarely done. In contrast, the next step of setting fish passage objectives, which concerns maintaining/restoring migration at the site scale, are common.

Often an ecological fish passage objective will relate to a target characteristic of the fish assemblage upstream and downstream of a barrier, such as maintaining or improving the diversity and abundance of native fish (Marques et al., 2018; Ordeix et al., 2011). In all stream restoration projects, a pragmatic approach is to aim for the least degraded and most ecologically dynamic state possible, given the regional context (e.g. catchment condition, adjacent land use history, flow regime and water quality (Palmer et al., 2005)). This 'guiding image' can then be used to guide restoration, and to set expectations for ecological responses. Transparency is an essential part of this process as there are many elements to native fish recovery, such as provision of environmental flows, habitat restoration and invasive species control (Baumgartner et al., 2021b).

There is increasing recognition that stream barriers permanently alter the upstream hydraulics from lotic to lentic, which can dramatically impact riverine fishes relative to pre-dam conditions (Greathouse et al., 2006; Mallen-Cooper and Zampatti, 2018) while favouring lentic and invasive species (Gillette et al., 2005). Therefore, it may be unrealistic to expect improvements in fish passage to completely restore/mitigate the pre-regulated fish communities. More realistic objectives are likely to include maintaining species diversity but at reduced abundances, which may meet some socio-economic objectives; or enabling upstream migrating fish access to remaining lotic habitats, such as in tributaries (Laub et al., 2018).

To set ecological objectives, the historical and predicted patterns in the distribution and abundance of fish need to be described (Fig. 2), which enables transparency in the recovery potential of fish.

Freshwater fish display a broad range of migration strategies and individual species can migrate at different times during the year, in response to a wide range of changes in flow and temperature. To set ecological objectives, this type of information can be used to develop conceptual models which identify the expected species and sizes (life-history stage) within the catchment (or biogeographic region), their seasonality of migration, diel movement patterns, migratory biomass, migratory direction (upstream or downstream) and the target range of river flows (Fig. 3) for migration. These ecological objectives are set at the riverscape or catchment scale and provide the framework for populations objectives. Fish passage objectives can then be set at the site scale, which directly inform fishway design and performance standards for evaluation.

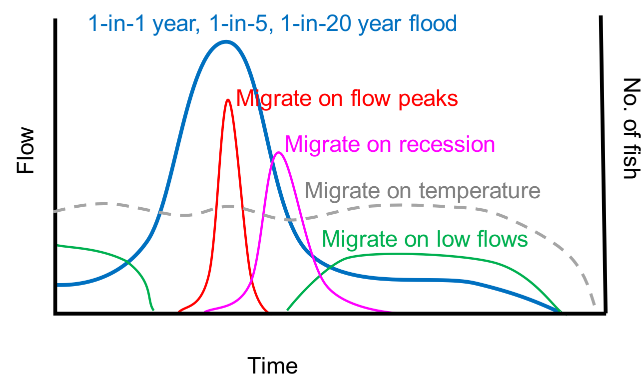

Fig. 3. A conceptual model of flow and fish migration for a lowland river system in south-eastern Australia. The blue curve shows the flow regime (peak flows could have varying timing of occurrence), and the other coloured curves show fish movement at different stages of the hydroperiod, or in response to water temperature rather than flow.

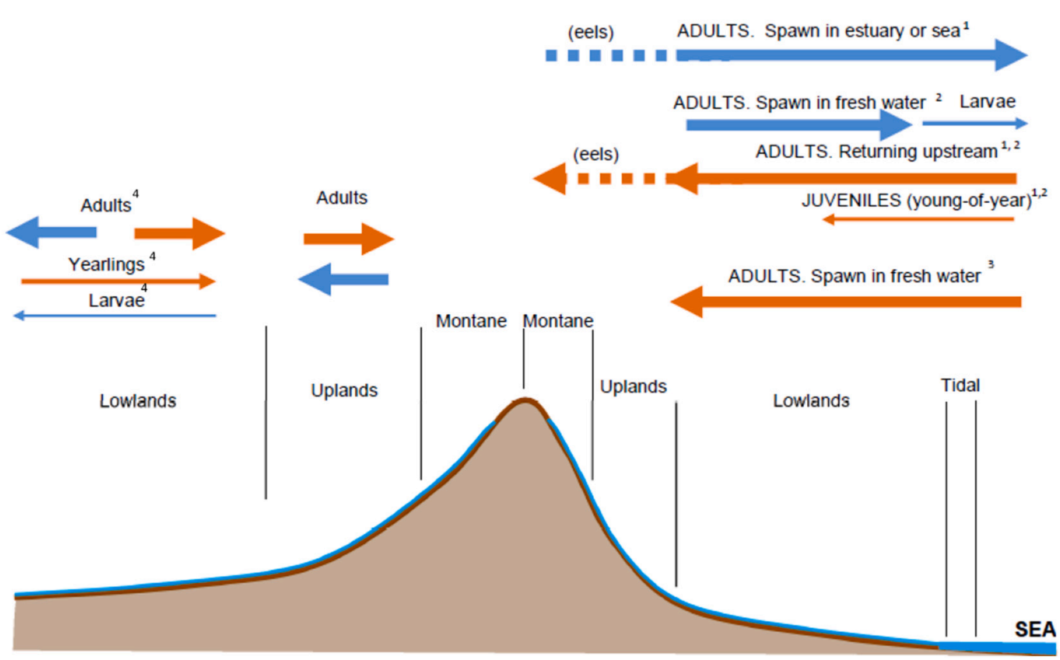

Fig. 2. A conceptual model of the common migrations of freshwater fish in south-eastern Australia. Blue arrows represent downstream migration and orange arrows represent upstream migration. [1]catadromous species, [2]amphidromous species, [3]anadromous species, [4]potamodromous species.

3.4. Population objectives

The ultimate purpose of fishways is to provide benefits for target species at the population level i.e. increased movement leads to increases in abundance and persistence above barriers. Consequently, it is necessary to set population level objectives, which can directly provide performance standards. For mobile species, there is likely to be a minimum proportion of fish that need to move through fishways to support population persistence and evolutionary potential (i.e. minimum viable population, or MVP (Beissinger and McCullough, 2002; Wilkes et al., 2019)). Modelling the MVP has been used to develop specific fish passage objectives and passage rates, based on the number of fish required to meet the ecological objective. For instance, 60–87% of upstream migrating adults of small species need to pass fishways in the Lower Mekong Basin but this increases to 80–95% when multiple dams are present (Halls and Kshatriya, 2009). Unfortunately, modelling is the exception rather than the norm that the design of fishways is based on quantitative models of how different levels of fish passage might impact fish population dynamics. Expert opinion can also be used to set performance standards that have population objectives. In the Columbia River in the US, the Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) process sets dam passage survival standards for downstream migrants of salmonid juveniles at 96% and 93% for spring and summer (Skalski et al., 2013).

3.5. Fish passage objectives

Fish passage objectives are at the fishway and site scale, and describe what fishway performance is required to meet the riverscape objectives of populations and ecology. Fish passage objectives often centre on the need to pass a required proportion of the fish assemblage, individual species, or life-stages without delay and over an expected range of flows. Ideally the selection of this proportion will be based on an understanding of the population dynamics of target fish species, potentially informed by quantitative modelling of different fish passage scenarios.

It is well recognised that fishway efficiency comprises attraction (fish locating and entering the fishway) and passage (through the fishway itself, including exit) (e.g. Cooke and Hinch, 2013). Poor entrance attraction causes migration delay which can have deleterious impacts for fish such as increases in predation or disease transfer following congregations at high densities (Agostinho et al., 2012; McLaughlin et al., 2013). Alternatively, delays may result in reduced feeding opportunities or spawning potential as fish miss optimal environmental conditions (Castro-Santos and Haro, 2003; Caudill et al., 2007; Nyqvist et al., 2017).

Management guidelines often publish 'allowable delays' for fish to find a fishway entrance. It is important to conduct research and monitoring to ensure that these are appropriate, with thresholds that are biologically meaningful given the life history of the target species. To do so requires information about how the migratory motivation, physical condition and mortality rates of fish might vary as a function of the time taken to find a fishway entrance and successfully migrate past the barrier - and to then identify thresholds which when exceeded result in deleterious impacts for fish (e.g. subsequent mortality, poor body condition, compromised reproduction). All of these aspects are likely to be species, site and perhaps even temporally specific factors and thus require a detailed conceptual model and data to inform fishway evaluation and performance standards.

Effective fishway design has included objectives of river flow and migration timing for over 60 years (Clay, 1961). Knowledge of the diversity of migration in relation to flow has increased and hence this needs to be specifically addressed in site-specific, conceptual models (e.g. Fig. 3), which informs performance metrics. Despite the inherent and established logic of integrating migration biology and flow in fishway design, often generic judgements concerning the fishway operational range are made prioritising economic rather than ecological considerations, which leads to inappropriate design criteria and performance standards. An operational range of 95% of flows sounds reasonable, but the flows that occur <5% of time can be critical for migration of some species. In the Murray-Darling river system in Australia, strong fish migration of high-flow and flood-cued species have occurred at flows that occur <1% of the time (e.g. golden perch *Macquaria ambigua*: Reynolds (1983); Koster et al. (2017)) and can be characterised by large migratory biomass (Mallen-Cooper and Brand, 2007). Elsewhere, floods also trigger fish movement in South America, Africa and along the Mekong River (Baran, 2006).

It is important to also acknowledge that some small bodied-fish and juveniles can migrate on the more common low flows (e.g. Barrett and Mallen-Cooper, 2006; Stuart and Marsden, 2021). Nevertheless, these low flows can be impacted by diversions at tidal barriers in dryland regions with coastal settlements – an impact that is likely to be accentuated by climate change. These low river flows at the tidal limit can be key periods for migration of juvenile diadromous fishes (Stuart and Berghuis, 2002); in this example, minimum fishway flow would become a critical hydraulic performance standard for ongoing inspections and operation. In summary, a conceptual model of life cycles and migration ecology that is bioregion and site specific is essential to develop appropriate fishway design criteria and relevant performance standards.

4. Developing fishway performance standards

As noted earlier, there are three types of performance standards that apply at three spatial scales: socio-economic standards at the riverscape scale; biological standards to riverscape, site and fishway scales; and hydraulic standards that apply at the site and fishway scales (Fig. 1). Socio-economic and population objectives can directly inform metrics and performance standards at a riverscape scale, independent of the fishway design and site-specific evaluation.

Biological performance standards at the site and fishway scale are derived from the fish passage objectives, based on the local fish ecology, site hydrology and conceptual models. The overarching definition of performance at these scales is the degree to which migrating fish can: (1) quickly locate and enter the fishway i.e. attraction efficiency, (2) efficiently pass through the fishway (upstream or downstream, i.e. passage efficiency) and (3) exit successfully (Roscoe and Hinch, 2010). These components underpin biological performance standards for the site and fishway (Table 1).

Hydraulic performance standards are designed according to the fish that approach and ascend the fishway (Rajaratnam et al., 1986). They should preferably be developed from laboratory and field evaluations of fishways with experimental manipulations of hydraulics and tests of the ability of fish to pass under different conditions (Castro-Santos et al.,

Table 1
Biological and hydraulic performance indicators for fish attraction, passage and exit.

	Performance Indicator	Attraction	Passage	Exit
Biological	Percentage passage of target species	✓	✓	✓
	Period of delay	✓		
	Accumulation of fish	✓	✓	
	Post passage mortality			✓
Hydraulic	Minimum/Maximum water velocity (head loss in pool-type fishways)	✓	✓	✓
	Minimum fishway flow (discharge)	✓	✓	✓
	Pool turbulence		✓	
	Minimum depth for target species	✓	✓	✓
	Flow vectors (no recirculation)	✓		
	Entrance discharge not masked by other flows	✓		
	Turbulence and water velocity from weir create *upstream limit of migration* at fishway entrance	✓		

2009; Mallen-Cooper et al., 2008; Silva et al., 2011). Within a fishway project, hydraulic performance standards are derived directly from fishway design and, as noted earlier, are used for wet commissioning and regular inspections for O&M. These standards also apply to attraction, passage and exit (Table 1). At a site scale they apply to attraction conditions of turbulence, upstream limit of migration, and recirculating flows (flow vectors), while at the fishway scale they apply to flow (discharge), water velocity, depth and turbulence.

When locating, entering, passing and exiting a fishway, fish can often encounter difficulties due to the inappropriate hydraulic conditions inside the fishway in regard to water velocity, turbulence and flow vectors (Calluaud et al., 2014). The design hydraulics of the fishway must ensure adequate dissipation of the energy of the water and offer resting areas for fish; the suitability of these different hydraulic regimes and water velocities will depend on the size and swimming ability of the target species (Santos et al., 2012; Table 1).

The hydraulic performance standard of head loss is an important surrogate for maximum water velocity (Table 1); it is a rapid, simple measure and if the head loss exceeds a standard, it is likely the target species cannot ascend the fishway. Fishway flow would seem an obvious standard that does need to be checked, but this can be an issue where flow is diverted for consumptive needs. Fishway depth (Table 1), which can be affected by silt or weir operations, is important to ensure large fish are able to move through a fishway without physical/hydraulic limitations (Katopodis et al., 2001; Santos et al., 2014; Thiem et al., 2011).

5. Case studies

To illustrate the contemporary application of fishway performance standards we examine four case-studies with: i) no performance standards; ii) a generic fish passage standard; iii) a comprehensive set of standards, but not all applied; and iv) performance standards being retrospectively developed for a structure that has been in operation for >50 years.

5.1. High-discharge, tropical South-American river, hydropower dam: Paraná River, Engineer Sérgio Motta Dam (Brazil)

The Engineer Sérgio Motta Dam (formerly known as the Porto Primavera Dam) and fishway is located in the tropical Parana River, Southern Brazil. The dam is 22 m high and was built for flood control, navigation and created a head differential to support a hydroelectricity scheme (Wagner et al., 2012). The fishway (weir and orifice type) was built between 1999 and 2001, is 520 m long, with 50 concrete weirs forming the 5 m wide by 2 m high pools (Wagner et al., 2012).

Celestino et al. (2019) reports that the fishway was installed to allow migratory fish access to tributaries upstream and maintain longitudinal connectivity in a fragmented segment of the Paraná River. However, there appears to be no detailed information on the fishway performance requirements a priori to construction in either the peer reviewed or accessible grey literature. Performance monitoring a posteriori has occurred in numerous studies, on numerous fish species, using a variety of methods, including evaluation of attraction, passage, delay and persistence of populations upstream but none are measured against a priori or a posteriori performance standards (Celestino et al., 2019; Gubiani et al., 2007; Makrakis et al., 2007; Volpato et al., 2009). These studies did not compare the results against any performance standards.

This case study highlights:

- Where performance standards and metrics are not explicit then the reader (or owner/manager) are unable to undertake a quantitative evaluation on whether the fishway is effective, or requires adjustment, or replacement.
- Where performance standards and metrics have been considered these need to be made available in the accessible literature.

5.2. High-discharge, tropical Asian river, hydropower dam: Mekong River, Xayaburi Dam (Laos PDR)

The 39 m high Xayaburi Dam was built between 2012 and 2019, on the middle reaches of the tropical Mekong River in Laos PDR. For upstream-migrating fish there are two pool type fish ladders provided; one is located on the left river bank (800 m long) while another is located near the spillway-powerhouse (600 m long) (Team Consulting Engineering & Management Co. Ltd., 2008). Downstream-migrating fish were provided with a surface bypass collector at the trash screens in front of the turbines, and 'fish-friendly' turbines (Baumann and Stevanella, 2012; Raeder and Thanakunvoraset, 2018); although we note that the latter term is mainly used to acknowledge design attributes that may reduce fish mortality but there is little or no data applicable to native fishes. It is arguably the largest fishway complex on any tropical hydropower dam.

The geopolitical context is that Xayaburi Dam was the first hydropower project on the mainstem Mekong River in the lower Mekong Basin which supports an international freshwater fishery that produces 1.3 to 2.7 million tonnes of fish and other aquatic animals per year. This context informed the overarching socio-economic objective of fish passage at the dam, which is to minimise impacts on transboundary fish resources (Mekong River Commission, 2019). No metrics or standards were developed or applied to this objective, which would be too difficult given the complexity, natural fluctuations, and other impacts on the fishery. Instead, a fish passage performance standard of 95% passage was developed by the Mekong River Commission (MRC) and agreed to by the four member countries. The MRC did population modelling of major migratory species, incorporating fish passage and turbine mortality, assuming the turbines were unscreened, and fish passed through the turbines. The modelling suggested that 95% passage for one dam was sufficient to maintain populations, but that the cumulative turbine impacts of two dams meant populations of medium and large-bodied fish were not viable, regardless of upstream passage effectiveness while small-bodied fish required 80–95% passage at two dams (Halls and Kshatriya, 2009).

The fish passage objectives for the Xayaburi Dam were to maintain upstream and downstream fish passage (Team Consulting Engineering and Management Co. Ltd, 2008) for the whole fish community (900–1100 species (Hortle, 2009)), to meet a generic MRC 95% standard. Objectives included passage of small (<200 mm long), medium (200–1000 mm) and large-bodied fishes, (to 3 m long) (Baird, 2006; Baran et al., 2011). Presently, field evaluation is occurring.

This case study highlights:

- The challenge of setting a generic fish passage standard (i.e. 95% passage) and then measuring these in a large tropical river with high fish biodiversity with widely varying migratory ecology.
- Whether or not the generic standard (i.e. 95% passage) is applicable at multiple barriers for achieving the desired population and ecological objectives, reiterating the need for monitoring and/or modelling populations.
- The importance of applying performance standards at a catchment scale rather than an individual site scale.

5.3. Low-discharge, southern temperate river, low weir: Yarra River, Dights Falls Weir

Constructed in 2012, near the tidal limit of the temperate Yarra River in Victoria, southern Australia, the ecological objective of the 1.85 m high Dights Falls vertical-slot fishway is to restore connectivity to upstream habitats for the whole fish community (up to 18 native species). The ecological emphasis, however, was on diadromous species, which included small fish (25–80 mm long) mostly juvenile catadromous species. Medium-and-large-bodied fishes (150–1100 mm long) were mostly sub-adult and adult catadromous species. Downstream passage was also considered with water released by a fixed crest spillway into a deep plunge pool (depth was 55% of head differential) where the hydraulic cushion excluded rocks and other hydraulic dissipater structures.

A comprehensive list of a priori performance standards were developed by one of the authors (IS), which included metrics for attraction and passage (Table 2). These were not published or publicly accessible. No a priori standards were set for fish populations, although a clear objective was restoration of diadromous species upstream of the weir; and no metrics were considered for socio-economic objectives, which could have included Indigenous cultural values or recreational fishing values. Fish populations have been monitored upstream (Amtstaetter et al., 2015) but no performance standards have been set. Although the standards were comprehensive, only a small number were applied (Table 2), mainly due to available resources.

This case study highlights:

- The initial emphasis on site-scale performance metrics and standards, which is very common in fishway science.

Table 2
A priori biological performance standards for Dights Falls vertical-slot fishway. Note that there were no a priori standards to maintain fish populations in the Yarra River upstream of Dights Falls apart from generically restoring connectivity for the full size and species range.

Performance standard			
Proposed	Comment	Applied in Wet Commissioning and Annual Inspections	Applied in Biological Assessment
Attraction			
Biological performance standard			
• Attraction of 95% of each migratory life stage of each species from 25 to 400 mm long	Difficult to apply to species with low abundances		✓ (common species only)
• Period of upstream migration delay: <1 day for full range of flows	Useful, but resource intensive. It is important for juvenile diadromous species subject to predation downstream of weirs. Tracking methods for small fish (< 50 mm long) not accurate.		
• No significant accumulation of fish below weir (for upstream migrants)	Useful, but resource intensive and impractical in high energy rock spillway		✓ (common species only)
Hydraulic performance standard			
• Minimum and maximum entrance head loss of 0.05 m and 0.09 m	In internal Design Report, not publicly accessible.	✓	
• Minimum approach depth of 0.3 m	In internal Design Report, not publicly accessible.	✓	
Passage (in fishway channel)			
Biological performance standard			
• Passage of 95% of each migratory size class (life stage) of each species from 15 to 400 mm long	Difficult to apply to species with low abundances		✓ (common species only)
• No accumulation of fish in fishway.			✓ (common species only)
• Maximum migratory biomass can pass fishway	Yarra River is a small, cool temperate, southern hemisphere stream that is considered unlikely to have a high biomass; so not considered a limiting factor in design. Potentially useful in other larger rivers, but resource intensive.		
• No energetic cost, or raised stress, disease, injury, predation risk to ascending fishway	Useful, but resource intensive. Not considered a high priority question for evaluation.		
Hydraulic performance standard			
• Maximum pool head loss of 0.075 m (+/− 15 mm)		✓	
• Minimum pool depth of 1.0 m (intended for maximum expected fish length of 400 mm long, and eels up to 1000 mm long)		✓	
EXIT (and continue migrating upstream)			
Biological performance standard			
• Safe exit of 95% of each migratory life stage of each species	Low likelihood of fallback over weir crest; no hydropower or irrigation outlet channels. Not used as a performance standard.		
• No post-passage mortality	Mortality considered unlikely, so not used as a performance standard		
Hydraulic performance standard			
• <20 mm head loss across the trash rack		✓	
Downstream passage			
Biological performance standard			
• No significant accumulation of fish above weir (downstream migrants)	Not assessed due to resource limitation		
• < 2% mortality passing over weir and through tailwater	Not assessed due to resource limitation		
Hydraulic performance standard			
• Minimum depth over weir crest of 0.3 m		✓	
• Plunge pool depth > 50% of the overall head differential	Needs assessment, to demonstrate survival rates		
Fish populations above and below the barrier			
Biological performance standard			
• Species richness, abundance and size distributions similar above and below the barrier			✓ (common species only)
• Success of trophic migrations (e.g. spawning and dispersal) maintained	Needs assessment may be aspirational due to practicality and budget limitations		
• No population cost (e.g. depressed recruitment)	Needs assessment may be aspirational due to practicality and budget limitations		

- The absence of socio-economic metrics, also common in fishway science.
- The recognition that population metrics needed to be included.
- The high resource demands for evaluating some performance standards and metrics mean these remain aspiration (i.e. energetic cost of fish passage, potentially raised fish stress levels, increased disease or predation) and their contribution to understanding population and ecological objectives needs to be carefully evaluated.
- For some sites and species there remains an inability to determine if the performance metrics have been met i.e. attraction efficiency of small fish species (< 50 mm long).
- Where performance standards and metrics have been considered these need to be made available in the accessible literature.

5.4. Moderate discharge, northern temperate river, moderate-height diversion weir: Seton River, Pacific Northwest: Seton Dam

The Seton River is a tributary of the mighty Fraser River which is the largest producer of Pacific salmon in Canada. The Seton Dam and associated fishway was constructed in 1956 as part of the expansive Bridge River Hydroelectric Complex near Lillooet, British Columbia. The 7.6 m high Seton Dam is positioned on the Seton River and forms an upstream impoundment (Seton Lake) to divert water to hydropower turbines on the Fraser River 4 km away and just downstream of the Seton River confluence. Olfactory cues from the turbines at the Fraser can serve as a source of confusion for given that fish encounter that olfactory bouquet before they reach the actual confluence with the Seton River servings as a potential migratory delay. The fishway is incorporated into the dam and has a vertical slot pool configuration. The 106.7-m-long fishway consists of 32 pools separated by concrete baffles and makes two 180° turns and thus has two primary corner turning basins. Fish ascending the fishway gain an elevation of 8.22 m (grade of 7.5%). The fishway is used for upstream passage by sockeye salmon, coho salmon, chinook salmon and pink salmon (in odd years) that have travelled ~350 km upstream from the Fraser estuary. The fishway and dam was one of the earliest to have dedicated fishway attraction flow, of 5–10% of outflows, partly because it is located 4 km away from the major discharge from the powerhouse. This also set a measurable hydraulic performance standard.

Salmon (varying by species and population) spawn in Seton Lake, the Portage Creek, in Anderson Lake, or in Gates Creek, all of which are upstream of the fishway. The dam is located on the ancestral lands of the St'at'imc peoples which are governed by the Lillooet Tribal Council.

Because the fishway was built over 60 years ago, it is not surprising that there were no rigorous a priori performance standards at time of construction. However, the infrastructure owner (BC Hydro) has since engaged in extensive efforts to both study the effectiveness of the fishway and identify opportunities to modify infrastructure or operations to benefit salmon and the people that depend upon them. Indeed, the St'át'imc people negotiated a Settlement Agreement with the Province of British Columbia and BC Hydro (in 2011) that provides mitigation, compensation and an ongoing long term relationship to address their grievances related to the construction and operation of existing BC Hydro facilities including the Seton Dam and fishway. Extensive collaborative research has occurred with Indigenous governments, academics, parliamentary governments, environmental consultants, and BC Hydro. That work has quantified attraction and passage efficiency as well as tracking fish after fishway ascent to understand success at reaching spawning grounds and spawning success. In general, fishway ascent is not overly challenging (Pon et al., 2009, 2012; Roscoe et al., 2011), however, fish tend to have difficulties finding the entrance and can expend significant time and energy attempting to locate the entrance due to complex flows (Burnett et al., 2014) after potentially encountering competing flows from the powerhouse 4 km downstream. Work has also revealed that there are post-passage consequences for fish which engage in high levels of anaerobiosis before or during passage; those fish are less likely to make it to spawning grounds (Burnett et al., 2014). Modifications to flows that enable fish to more easily locate the fishway entrance have improved survival to spawning grounds rather dramatically (Burnett et al., 2017; Bett et al., 2022).

Beginning in 2008 BC Hydro began working on a Fish Passage Decision Framework with a second version released in 2018 (BC Hydro, 2018). Although developed for planning new fish passage facilities, the framework is also relevant to existing facilities. Environmental feasibility studies are conducted to determine if fish passage plan objectives developed collaboratively with relevant stakeholders and rights holders can be met. Environmental feasibility includes considerations of the potential for stock enhancement, quality and quantity of habitat, and the ecological risks and benefits of the plan. Other considerations include the costs of the plan and the benefits in terms of ecological (e.g., productivity), conservation, Indigenous cultural and other societal benefits (e.g., tourism, education). Interestingly, the Bridge-Seton Watershed Action Plan (FWCP, 2017) does not list any specific concerns related to fish passage at Seton Dam which is somewhat surprising based on previous research. However, more broadly there are recommendations related to restoration and included in that is the recommendation to include indicators and performance standards for effectiveness monitoring. The aforementioned Settlement Agreement with the St'át'imc government included verbiage that parties would determine appropriate strategies, if any, to be implemented in an effort to mitigate the factors impeding upstream fish passage at Seton Generating Station. In a forthcoming Water Use Plan Order Review a suite of "performance measures" are being developed that may extend to fishway performance. At the new Site C Dam on the Peace River in northeastern BC, clear a priori performance standards were developed with diverse partners and have informed the design of the facility and planned effectiveness monitoring (see BC Hydro, 2012). Efforts continue to develop performance standards for the fishway at Seton Dam.

This case study highlights:

- Many dams with fishways have existed for decades, well before performance standards were being considered
- The Seton Dam and Fishway are such an example where the construction occurred in 1956 with little biological assessment of fish passage until 50+ years later
- A Fish Passage Framework has been developed but it remains unclear how it applies to existing facilities
- In British Columbia there are Indigenous rights holders and associated Indigenous governments that must be involved with identifying performance standards
- Given opportunities to refine fishway operations or infrastructure to enhance passage, having clear targets and standards would help with discussions about various (and often complex) trade-offs (e.g., generation, flow releases, water temperature and total dissolved gas management) that also need to be considered
- Fish passage performance standards will likely be embedded within broader restoration plans for the watershed and may be implied rather than specific to passage
- Decisions on operational strategies will need to balance a suite of performance measures that extend beyond fish passage

6. Discussion

6.1. Application of performance standards

In our review of recent papers on fishway efficiency 97% and 44% measured biological and hydraulic performance indicators, while only 8% set a priori biological performance standards and 15% set a priori hydraulic performance standards. The tone of the papers often used qualitative language in the discussion such as "improved", "good", "high" for efficiency – inferring that a fishway did, or did not, provide acceptable efficiency - but the language is non-committal, while threshold standards were not articulated, and a binary conclusion of effectiveness, were absent. These results illustrate that while many recent studies are measuring fishway performance using biological and hydraulic indicators, very few are relating these measures to performance standards. This is a significant omission in fishway science, and hinders transparent assessments of fishway performance.

We acknowledge that performance standards can be difficult to apply. Most studies focus on site-specific measures of the fishway, but it is essential that these be combined with riverscale metrics of populations or socio-economic values; otherwise it is unknown whether the fishway is meeting its original objectives, regardless of passage efficiency at the site.

6.2. Institutional and cultural barriers to the development and adoption of fishway performance standards

Fishways require a combination of engineering, hydrology, hydraulics and biology. A design team should incorporate expertise from across the disciplines but the end result is primarily a civil engineering project. The culture of consulting civil engineers is to problem solve, be creative, produce cost-effective innovation, and deliver CAD drawings for construction, sometimes with a design report; it is not necessarily to publish in refereed journals.

Scientists are also problem solvers, but their end results reflect a culture of publication in refereed journals. The authors have been involved in many fishway design projects, as scientists, but the inputs to these projects – including ecological and fish passage objectives, and design criteria - are not the substance of refereed papers. Hence, the accessible outputs on fishway design almost universally reflect the refereed papers which are mainly on assessment of function after construction, or of experimental fishways. These usually describe the hydraulic characteristics of the fishway but not the logic of design or expected performance. The objectives of the fishway, which are needed to develop performance standards (Fig. 1), remain in the inaccessible grey literature in design reports.

We consider this is a global institutional and cultural barrier to the development and adoption of fishway performance standards. We propose that a useful approach to overcome this would be that: i) performance standards be developed and documented a priori in the design phase, as per Fig. 1; and ii) a publicly accessible fishway database be used to document performance standards. The CanFishPass for Canada provides a good example to build on (Hatry et al., 2013).

6.3. The potential risks of using performance standards

The benefits of performance standards are very clear: inadequate performance can identify where fishway replacement is required; or poor performance can identify where improvements can be made. Nevertheless, it is important to reflect on some potential risks of their use. One is that innovation is curtailed, as standards preclude the use of some, potentially more experimental, methods and designs (Baumgartner et al., 2020; Silva et al., 2018). Practitioners may also be discouraged from working in situations where unrealistic 'gold standards' are set that can never be met (Higgs et al., 2018b). Discussion about the recent publication of the international standards for ecological restoration illustrates some of the complexities, and pros and cons of using standards including reducing the risk of failure and improving decision making but while simultaneously curtailing innovation (Gann et al., 2018; Higgs et al., 2018a; Higgs et al., 2018b). We agree that it is important that standards are set using general principles (Higgs et al., 2018b) but also that standards allow metrics to be set that measure progress towards specific objectives (Gann et al., 2018). This latter point is critical for fishways, especially in terms of the number of fishes that must pass to achieve ecological objectives such as the development of self-sustaining native fish populations, as examples from America, especially on the Columbia River, demonstrate (Skalski et al., 2013). Transparent communication of risk to stakeholders and rights holders helps alleviate potential roadblocks to the use of performance standards.

6.4. Monitoring and adaptive refinement of performance standards

Setting performance standards for individual fishways will be beneficial and provide clear metrics for monitoring (e.g. Mallen-Cooper, 1999). It is important that standards account for differences among species at the same fishway based on their life history requirements. Standards may also vary for the same species at different fishways, even on the same system, especially if passage efficiency varies as a function of fishway type (Noonan et al., 2012).

In natural resource management, actions need to be monitored to assess progress towards objectives (Palmer et al., 2005) and allow scientists and practitioners to learn from previous projects. Fishways need to be assessed both in terms of site-specific performance standards and riverscale ecological objectives. Assessing fishway effectiveness only, such as the proportion of fish that ascend, is not a surrogate for the capability of the structure to maintain viable fish populations (Pompeu et al., 2012). It is also worth noting that often monitoring of fishways is not implemented or is not a licensing requirement (Birnie-Gauvin et al., 2019), and monitoring broader fish populations is not even considered.

If standards are not met, fishways can be replaced or modified. Numerous fishways have been replaced in Australia which were based on old inadequate salmonid designs (Mallen-Cooper and Brand, 2007; Barrett and Mallen-Cooper, 2006). Monitoring and performance standards provide a quantitative basis for modifications. The Dights Falls case study presented earlier provides an example - when it was initially completed, fish were not being passed during high flow events and so a third fishway entrance was added and the fishway now passes a diverse and broad size range of fish at a range of high and low flows (O'Connor et al., 2015; GHD, 2015; O'Connor, unpublished data). Adaptive refinement of standards is also important – performance standards should reflect changes in knowledge of fish population dynamics, which may increase or decrease the required fish passage efficiency at the sitescale.

6.5. Identifying areas of uncertainty and the need for future research

A major knowledge gap in developing performance standards is that the information needed to set the required parameter values is not available, especially when we consider that standards need to be set at the fishway, site, and riverscape scales (Fig. 1). Fishway performance standards need to be developed based on the life history of the fish community with achievable ecological objectives set by stakeholders and rights holders. Often standards are not set, or when they are, this is based on estimates from experts on the required proportion of fish needed to pass upstream – that is site-specific targets. These estimates tend to propose that very high (>90%) levels of passage are needed (Forty et al., 2016). However, if the ecological and fish population objectives are met with lower targets (e.g. 50%), fishways may be overengineered and more costly.

Some examples exist where performance standards have been set based on population models (e.g. Stich et al., 2019) and more studies like this are needed, to provide evidence that meeting a particular site-specific performance standard (e.g. % of fish passing in a timely fashion), leads to ecological objectives (e.g. maintenance of fish spawning stock). This is an aspirational target, especially in rivers with high species diversity, given the wealth of knowledge these population models require about the life history of each species. Research on life history and population demography of examples of riverine guilds could be a useful approach. There are always uncertainties in population models and these can lead to erroneous estimates and management decisions that, both from a design and operational perspective, are costly in terms of economic expenditure and failed conservation outcomes (Cooke and Hinch, 2013).

While there is considerable knowledge about the ability of a range of fish species to ascend fishways, far less is known about the degree to which fish can locate fishway entrances (Silva et al., 2018). For amphidromous species, the fundamental ecology and life history characteristics are also not well understood (Franklin and Gee, 2019). In biodiverse rivers, the small body size of many fish species precludes them for consideration for most tags (Swarr et al., 2022) and so their behaviour when approaching and ascending fishways remains a knowledge gap. A key aspect of designing effective solutions for fish passage is to know when fish are migrating, where they came from and going to. However, there are varying degrees of knowledge on fish migration for different species, with large gaps in our understanding particularly with regards to small-bodied fishes.

Another important knowledge gap is the fate of fish once they have moved upstream, which can be especially important where habitat conditions have changed for example from a lotic to lentic environment where impoundments upstream of dams can act as ecological traps (Pelicice and Agostinho, 2008) preventing downstream movement of eggs and larvae necessary to complete some fish life cycles (Birnie-Gauvin et al., 2019). Understanding of the expected ecological objectives and outcomes (i.e. performance standards) are needed to know which species need to be catered for, what size they will be at the time of migration, where passage should be provided in a catchment, and for what flow conditions the passage needs to be optimized. Failure to think critically about these factors for a given study/site has the potential to influence the choice of performance indicators or standards (e.g. % passage and attraction efficiency), which will impede the ability of science and monitoring activities to inform fishway design and operation, and ultimately improve aquatic ecosystems (Cooke and Hinch, 2013).

7. Conclusions

Setting performance standards is a critical but underdeveloped aspect of fishway design and assessment. We have presented a conceptual framework that illustrates how such performance standards sit within the wider process of objective setting, fishway design and assessment, and outlined key principles in the development of fishway performance standards. It is vital though to consider how the principles we have outlined can inform the practical setting of standards.

There are several key considerations that may help guide the implementation of performance standards. We have highlighted the importance of using empirical information (either from population models or field assessments) to help set performance standards but often this information may not be available, and there is often no opportunity to wait for it to be collected. What should happen in these circumstances? Firstly, the logic explained in Fig. 1 is still applied: ecological, population and socio-economic objectives and metrics are articulated and documented. Expert opinion (which could include Indigenous knowledge keepers, fisheries managers, recreational fishers, etc) is used to set performance standards at the site scale which, in the absence of quantitative population performance standards, will likely result in conservative design criteria. Hence, this is an environmentally conservative approach that maximises the performance of the fishway. Using this framework and articulating the high-level objectives will provide greater impetus to refine ecological models of movement and migration and integrate these with models of population dynamics.

A second key consideration is the recognition that performance standards need to be linked to ecological objectives and the level of performance may vary considerably based on that objective. For instance, often fish passage of 90 or 95% are used as standards but significantly lower levels may be required to sustain populations of some species (e.g. 30% - Franklin et al., 2018). Performance standards for maintaining genetic diversity may also be lower than the typically used standards. For instance, in guidelines for quantifying extinction risk, the IUCN have created the "50/500" rule which suggests that a minimum population size of 50 individuals is necessary to combat inbreeding, and minimum of 500 individuals is needed to reduce genetic drift (Mace et al., 2008). Explicitly linking standards to ecological objectives will help better guide the required level of fishway performance.

Given that setting performance standards is challenging, especially when empirical information is limited, it is also important to reflect on the potential transferability of standards between fishways. For instance, it may be possible to use a similar approach to multi-scaled environmental monitoring networks (Jones et al., 2010) where research and monitoring is undertaken to set performance standards at a subset of fishways embedded within a wider network of fishways where these standards are applied, and more basic compliance-style assessments are undertaken to assess performance against these. A critical element here will be to understand the likely context dependency of results (i.e. why disparate results might be observed in different locations or conditions (Catford et al., 2021), and the degree to which standards from one fishway may be able to be used, or need to be modified, to be applied at fishways in similar environmental contexts. We recognise that every fishway is different but there may be sufficient similarities (e.g. within ecoregions) to be able to apply similar standards in some instances.

Fragmentation of freshwater ecosystems is a major threat to biodiversity and fishways are an important tool in mitigating the effects of reduced stream continuity and connectivity. Fishway science is continuously evolving, and an increased focus on setting, evaluating, and adaptively altering performance standards is an important future development. Ideally such performance standards will be closely linked to design, operation and maintenance guidelines which will enable fishways to fully optimise their function in ecosystem restoration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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