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A framework for functional fish passage decision-making

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Abstract There are millions of built structures existing today in thousands of rivers. While these structures provide important services to society, e.g., power, transportation, and water for drinking and irrigation, the structures are not without consequences for provisioning the whole of a rivers' goods and services. A major issue for these structures is their creation of barriers for fish passage. While most provide some form of fish passage, the solutions are restricted to economically important species and barriers in isolation. We are slowly accepting that there are broader ecological consequences of barriers and more holistic approaches are emerging for the planning and managing created barriers in river ecosystems. We develop a holistic and adaptive, fish passage decision-making framework that uses key science questions to inform and support the development of successful fish passage management plans for a barrier and the river ecosystem. The framework builds from the biological needs of fish for functional passage, which can then support the complex social and economic considerations that are entwined in a comprehensive management plan. The framework uses a multi-species, ecosystem focus, embraces uncertainty, and embraces an adaptive approach. We recognize this approach advocates for a paradigm shift in fish passage decision making and management, but cracks in the old paradigm are emerging, and it is imperative that operators, regulators, rightsholders, stakeholders, and science keep working together to build this new paradigm that embraces a whole ecosystem approach.

Keywords Fish passage · Structured decision-making · Fisheries management

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Introduction

People have built dams, weirs, canals, and locks along rivers for thousands of years, and millions of built structures exist today in thousands of rivers (e.g., Lehner et al. 2011; Zarfl et al. 2015; USACE 2018; Belletti et al. 2020; Lin et al. 2020). These structures have and still provide important services to society such as electrical power generation, transportation routes, and water for drinking and irrigation. However, they are not without consequences for the entirety of a rivers' goods and services that society desires (Barbarossa et al. 2020; Rideout et al. 2021). Infrastructure in rivers inevitably creates barriers for resident and transient animals and plants that rely on unimpeded access to habitats to complete their life cycles (Liermann et al. 2012; Jones et al. 2020a). Traditionally, barrier challenges have focused on economically important fish species and even more narrowly on the ability of fish to move up and/or downstream of a single barrier. However, scientists, regulators, and stakeholders are becoming more aware of the broader ecological consequences of barriers in rivers (Bem et al. 2021; Tonkin et al. 2021) and the importance of understanding these when building new barriers or mitigating existing barriers (Poff and Olden 2017; Wilkes et al. 2019). Full protection of a river's goods and services demands that we begin to incorporate a more holistic approach when we plan and manage river ecosystem (e.g., Ziv et al. 2012; McLaughlin et al. 2013; Poff and Olden 2017; Harper et al. 2021; Torgersen et al. 2022).

Broadly, the history of fish passage at barriers is a sad story (Brown et al. 2013; Kemp 2016). Fish passage is often a tertiary consideration, low in priority behind needs for power generation, irrigation, transportation, or water supply (e.g., Zarfl et al. 2015; Chung et al. 2021). When fish passage structures are created, decisions regarding what species and what proportion of the population to pass are notoriously difficult to make (Roy et al. 2018; Venus et al. 2020), and often relied on subjective, unquantified, and narrowly defined objectives overshadowed by economics (Birnie-Gauvin et al. 2018; Silva et al. 2018). Where comprehensive watershed or fisheries management plans exist (e.g., Migratory Fish Management and Restoration Plan for the Susquehanna River Basin, Miller et al. 2010), aspirational goals and measurable objectives can guide decision-making for fish passage during dam construction, relicensing, or removal (Roy et al. 2018; Song et al. 2020). But comprehensive plans are difficult to achieve and mostly absent. It is common for fish passage decisions to be restricted to a single barrier of interest for one or a limited number of target species (Mallen-Cooper and Brand 2007; Birnie-Gauvin et al. 2018) and often where ecological and economic values and objectives are at odds (Ziv et al. 2012; Rahel and McLaughlin 2018).

Herein, we develop a science-based, fish passage decision-making framework as a guide for improving fish passage outcomes for a river ecosystem and the entirety of its goods and services. The framework integrates emerging fish passage science of the existing literature (see, for example, Lennox et al. 2019) into a structured decision-making process for multi-species, functional fish passage as discussed by, for example, Winemiller et al. (2016) and Birnie-Gauvin et al. (2018). The framework is based on the biological needs of fish for functional passage compiled as questions, which is the prelude to the complex social and economic considerations that are entwined in a comprehensive watershed or fisheries management plan as demonstrated by Roy et al. (2018) and Venus et al. (2020). The most relevant of the reviewed literature is summarized in Dolson et al. (2021). This framework is currently being applied in the Wolastoq | Saint John River (Curry et al. 2020), and we will report on successes and challenges as the project progresses.

The framework background

Overview

Barriers that provide fish passage in rivers have achieved some success (e.g., Williams 2008; Silva et al. 2018), but mostly threaten the persistence of freshwater fishes around the world (Olden 2016; Barbarossa et al. 2020). Whether dealing with existing or new fish passage structures, a more comprehensive approach to fish passage decision-making would significantly enhance the sustainability of commercially, culturally, and intrinsically valued fishes and the services they support in a river basin (e.g., Poff and Olden 2017; Birnie-Gauvin et al. 2018; Silva et al. 2018; Curry et al. 2020; Tonkin et al. 2021). This requires engagement of government, regulators, rightsholders (i.e., Indigenous peoples), scientists, and dam operators and necessitates a system-wide approach to barrier and passage assessment. We have ample scientific evidence that decision-making needs to overcome the prevalence of evaluating one barrier or one species in isolation of the whole river ecosystem (e.g., Winemiller et al. 2016; O'Hanley et al. 2020; Duarte et al. 2021).

Fish passage efficiency and management at dams

"Fish passage" has a myriad definitions. We use "functional fish passage" which is a passage definition based on ensuring sustained healthy, naturally reproducing populations (e.g., Nyquist et al. 2017; Silva et al. 2018) in the presence of a barrier. The definition has four principles: (1) passage must be safe, causing minimal stress, injury, and mortality; (2) passage must be effective, a sustainable proportion of individuals must be passed; (3) passage must occur with minimal delay, fish must be able to reach their destination within necessary windows of ecological and physiological requirements; and (4) passage must result in achieving the ecological endpoint for the migration or movement (e.g., spawning, rearing, emigration, overwintering, etc.) that sustains the population.

Emerging science has challenged the underlying assumption that single barrier solutions provide "functional" fish passage (e.g., Mallen-Cooper and Brand 2007; Pompeu et al. 2012; McLaughlin et al. 2013; Government of Ontario 2021). It has been repeatedly shown that ineffective or maladaptive passage options, including lack of consideration of useable and available upstream habitat (quality and quantity), can harm a population as much as a complete barrier without passage (e.g., Pompeu et al. 2012; Wilks et al. 2019). This relates mostly to upstream passage because it is frequently assumed that downstream passage is not required or will be successful via spillways or hydropower units (turbines). The consequence of not considering these species-specific needs and the broader population, community, and ecosystem impacts leads to certain failure for the species' and river system, e.g., passage delays, unplanned fallback across the barrier, increased predation risks, reduced fish health, loss of individuals from self-sustaining downstream populations, introducing invasive species and pathogens, and the negative impacts of cumulative mortality in multi-barrier systems (see among many examples, Pelicice and Agostinho 2008; Dugan et al. 2010; Kemp 2016; Cooper et al. 2021).

Research on passage efficiency typically evaluates success based on a limited number of target species and their ability to navigate the passage structure, regardless of achieving or not, ecological endpoints (Birnie-Gauvin et al. 2018; Silva et al. 2018). Target species are commonly commercially valuable and obligatory migratory species; little to no consideration is given to other fish species which often differ in body type, behaviors, movement motivations, and swimming capabilities (Kemp 2016; Jones et al. 2020b). Salmon (genera *Oncorhynchus* and *Salmo*) have been at the center of fish passage research worldwide, and not surprisingly, salmon-centric designs of fishways have been applied at many (arguably most) barriers (e.g., Katopodis and Williams 2012; Lira et al. 2017; Harris et al. 2017) regardless of the freshwater or diadromous fish communities present and which often differ from salmon in many ways. Not surprisingly, these fishways have largely been ineffective for non-salmon species (Noonan et al. 2012), lead to population declines (Pelicice and Agostinho 2008), and have created a cascade of unplanned, ecological impacts (Wilkes et al. 2019).

Depending on the jurisdiction, the regulatory environment may be a hindrance to successful fish passage management. Publicly accessible license conditions, permits and permitting processes, and management plans that address fish passage decision-making typically focus important commercial or recreational fisheries and offer limited options for accommodating opposing objectives between regulators, power operators, rightsholders, and stakeholders (Song et al. 2019; and see review by Dolson et al. 2021). Licensing and permitting requirements of many jurisdictions restrict the scope of passage discussions to single barriers, rely on qualitative data, consider a limited number of species, or lack overarching management goals and objectives (e.g., Mossop and Higgins 2012). In addition, an approval or license to operate often applies for the lifetime of the facility without options for future reviews of passage success and failures and adaptations to original plans. Where adaptive management processes are required as part of an approval or license, post-construction and operational monitoring results are often not publicly available, and what, if any, adaptive mitigation has been required or successful is largely unknown (Birnie-Gauvin et al. 2018; Silva et al. 2018), although modelling approaches are emerging to examine multifaceted, management options (Song et al. 2020; Venus et al. 2020).

There are a growing number of examples that demonstrate a more holistic and adaptive approach to fish passage decision-making and management. Under the Water Framework Directive (WFD), countries in the European Union can enact fish passage decisions and management actions geared towards ensuring all barriers that significantly hamper migration for diadromous species are mitigated or removed by 2027 (Breve et al. 2014). Similar approaches to evaluating passage decisions within the scope of watershed or fisheries management objectives and against defined ecological criteria are emerging globally, e.g., Australia (O'Connor et al. 2015), Canada (FWCP 2016), Iceland (Gíslason, 2016), New Zealand (Franklin et al. 2018), South America (Pompeu et al. 2012), Southeast Asia (Baumann and Stevanella 2012), and the USA (US Department of Energy 2016).

The passage decision framework

Based on our experiences and ongoing conservations among global experts (e.g., Silva et al. 2018; Lennox et al. 2019), we concluded that there was a need for a science-based, decision-making framework that uses a series of guiding biological and ecological questions to assess the need and targets for passage for species or guilds, especially in multi-barrier, multi-species, and multi-use rivers (e.g., Birnie-Gauvin et al. 2018; Silva et al. 2018). There have been many passage decision-making processes, e.g., each time a dam is built or renewed in USA or Canada (e.g., Mossop and Higgins 2012), and there are examples of fish passage decision-making models (e.g., Stich et al. 2019); however, there is no consensus, basic guideline to help practitioners build and execute effective decision-making.

Our proposed decision-making framework adopts a three-stage approach: Part 1: For each species likely to be impacted, assess the requirements to complete their life cycle, i.e., what species require passage?; Part 2: Assess the effect of passage on each population's resilience, e.g., sustained natural reproduction, and their provisioning of ecosystem services (e.g., indigenous fisheries), i.e., what proportion of a population should be passed; and Part 3: A decision-making process incorporating the outcomes of Parts 1 and 2. The framework is a synthesis of existing knowledge (the literature cited herein), our experiences with regulators, operators, and rightsholders at a large hydropower dam undergoing a renewal (Curry et al. 2020), conversations with practitioners worldwide (see Acknowledgements), and existing guidance documents (e.g., Bobrowicz et al. 2010; O'Connor et al. 2015; FWCP 2016; Wisconsin Department of Natural Resources 2017; Government of Ontario 2021).

Every waterway will have unique characteristics defined by the environment and species' ecology, socio-cultural values, and water resources usage. The fish passage decision-making framework presented considers only the science component that will be needed to support the undoubtedly more complex comprehensive management planning (e.g., Rodríguez et al. 2006; Moran et al. 2018; Song et al. 2021). The science component itself requires regulators, rightsholders, and stakeholders to first establish aspirational goals for the system that will guide the decision-making process. These goals direct the development of specific, measurable targets (or metrics) along with methods to evaluate target uncertainties that can be applied among a selection of passage scenarios; for example, the goals will identify species or guild(s) or representative species of a group or guild that require passage. These structural elements of the decision-making process are critical, but none more so than post-implementation monitoring to assess the effectiveness and success of decisions and actions taken to achieve functional fish passage.

Framework structure

Part 1: What species require passage

The initial step in the framework (Fig. 1) will guide the decision-maker's evaluation of what species require passage at a barrier. This is based on the biology of the species present and their life cycle requirements. Each system will be different ecologically with varied states of knowledge and data availability. In addition, a system may have a complex fish community or lack enough knowledge of extant species such that a fish guild approach may be a more appropriate

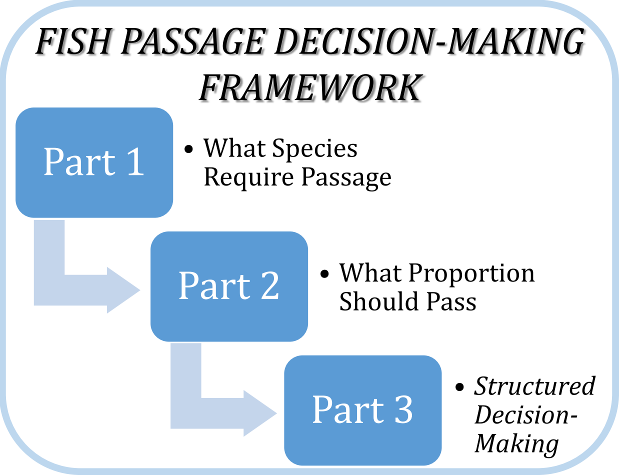

Fig. 1 A science-based fish passage decision-making framework

classification for passage needs (e.g., Welcomme et al. 2006; Wegschieder et al. 2020). This flexibility is an example of the adaptive approach that must be applied in this framework and for fish passage management in general. Part 1 is an assessment to (1) identify species or guilds of importance based on watershed, conservation, or fisheries management goals and objectives and (2) determine the ecological consequence of providing passage for the identified species/guilds. In the guiding questions, we generalize by using "species" knowing that questions may refer to individual species or guilds and using "system" to be the whole of the watershed as would be defined in the overarching management goals. An abbreviated example of the matrix of species and needs is given in Table 1 for the renewal of the Mactaquac Hydroelectric Generating Station (Curry et al. 2020).

Guiding questions

- What are the species and species-specific priorities in the system? This is a list of species that will be considered for passage, prioritized as may be necessary based on overarching management goals (Table 1).
- If species knowledge is limited or many species exist in a system, then can passage questions be applied to fish guilds defined by behavior in association with barriers in a river, e.g., benthivores approaching along the bottom (e.g., sturgeons), rheophilic classes (e.g., surface schooling river herring)?
- Is migration or movement across the barrier location known or assumed to be necessary for the species to carry out its life cycle?
- How much habitat of necessary quality and quantity exists upstream and downstream of the barrier location? This is asked for each life history stage and in a cumulative context in multiple barrier systems.
- Is the species present as a viable population(s), i.e., naturally self-sustaining, upstream, and downstream of the barrier location?
- How will passage impact viability of populations (positively or negatively) upstream and downstream of the barrier location, e.g., add habitat, or deplete downstream populations if no downstream passage is provided.
- What are the solutions and estimated costs for effective, functional fish passage up- and downstream for all life stages of the species?
- What is the upstream passage efficiency for the existing or planned fishway solution for each species and life history stage where applicable?
- What is the total mortality rate for downstream passage for each species and life history stage where applicable, for both direct and indirect mortality (e.g., severity and frequency of non-lethal injuries, delayed mortality)?

Table 1 An example of a species priority list for fish passage decision making from Part 1 of the proposed framework. An abbreviated example for the Saint John River | Wolastoq, NB; see Curry et al. (2020)

Species	Life history stage	Passage priority	Population status upstream	Population status downstream	Is downstream passage required (semelparous or special circumstances)	Predicted minimum number passing upstream annually	Upstream passage potential	Peak upstream movement	Technical solution: upstream (order of potential effectiveness)	Downstream passage potential	Peak downstream movement	Predicted minimum number passing downstream annually	Technical solution: downstream (order of potential effectiveness)	Special considerations (passage and ecological)
American shad	Adult	High	Unknown	Unknown	Required	< 1000	Possible	May–June	1. Ladder 2. Trap and truck	Unknown	Unknown	< 1000	1. Bypass/collection 2. Spillway	Mortality associated with trap and truck
American shad	Juvenile	High	Unknown	Unknown	Required	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	1. Bypass/collection 2. Spillway 3. Turbine	—
Atlantic salmon	Adult	High	Unstable	Unstable	Required	2000	Poor	June–October	1. Lift 2. Ladder 3. Trap and truck	—	—	—	—	Reservoir conditions
Atlantic salmon	Kelt	High	Unstable	Unstable	Required	—	—	—	—	Unknown	November	< 2000	1. Bypass/collection 2. Spillway 3. Turbine	Reservoir conditions
Atlantic salmon	Smolt	High	Unstable	Unstable	Required	—	—	—	—	Poor	November and May–June	< 100,000	1. Bypass/collection 2. Spillway 3. Turbine	Reservoir conditions
Atlantic sturgeon	Adults (> 1 m body length)	Passage creates substantial risk to species	None	Stable	Required	Unknown	Poor	July–August	Fish lift	Poor	July–August	Unknown	1. Bypass/collection 2. Bypass/lift	—
Atlantic sturgeon	Sub-Adults (< 1 m body length)	Low	None	Stable	Required	Unknown	Poor	July–August	Fish lift	Poor	July–August	Unknown	1. Bypass/collection 2. Bypass/lift	—
Atlantic sturgeon	Juveniles	Low	None	Unknown	Required	Unknown	Possible	Unknown	Fish lift	Poor	Unknown	Unknown	1. Bypass/collection 2. Bypass/lift	—
Atlantic sturgeon	Larvae	Low	—	Unknown	Unknown	—	—	—	—	Poor	July–August	Unknown	1. Bypass/collection 2. Spillway 3. Turbine	—

- What is the cumulative mortality rate across multiple barrier systems for each species?
- Is the existence of a reservoir(s) an ecological barrier or trap for a species passing upstream or downstream: what is the rate of mortality is associated with each reservoir? (e.g., Liew et al. 2016; Babin et al. 2020)
- What are the ecosystem consequences of either providing or restricting passage at a barrier location, e.g., predator–prey interactions, impact on unionid mussels' host-fish species, restricting/releasing invasive species, and/or pathogens or parasites (see, for example, McLaughlin et al. 2013; Zielinski et al. 2020; Cooper et al. 2021)?

Other biological or ecological questions may be relevant to a particular watershed or barrier such as the presence of regionally recognized, species at risk (e.g., Canada's *Species at Risk Act* or the European Red List of Threatened Species), or invasive species that are restricted by the barrier and may be released with the creation of a fishway up- or downstream (e.g., McLaughlin et al. 2013; Kreig and Zenker 2020). An importance, or weight, can be assigned to each question depending on the watershed and species needs. The answers to Part 1 can then be assembled as a decision matrix based on the likelihood of successful up- and downstream passage for each species or guild at each barrier and its reservoir and then cumulatively across the watershed. Uncertainty is guaranteed given the complexity of river systems and likely limits on existing knowledge and data. Rarely will a simple passage scenario exist or the time to build baseline ecological conditions prior to addressing the passage issue (e.g., Arnold et al. 2019; Curry et al. 2020). All uncertainty must be clearly documented; how it is addressed will depend on the river ecosystem and management process, i.e., unique to each river.

Part 2: What proportion of a population should be passed

The preferred, although utopian outcome, at a barrier is fully functional passage or 100% up- and downstream success for all species. However, it is understood that fish passage, even if efficient and effective, does not guarantee the existence of a naturally self-sustaining population nor a healthy population. In situations where passage is deemed to be required (Part 1), the bi-directional passage rates will need to be estimated and then decisions made regarding how many individual fish to pass (Part 2; Fig. 1).

Guiding questions (for each species/guild identified in Part 1)

- What is the estimated population size for the species up- and downstream of the barrier location?
- Does a population model with variability estimates exist? If not, then a model of some form will have to be created.
- What is the estimated productivity, e.g., egg-to-spawner production per area, for all available habitats up- and downstream of the barrier location(s)?
- How will fish productivity change with passage at the barrier location (and cumulatively)?
- What is the estimated mortality for each life history stage due to other factors, e.g., commercial, recreational, traditional harvests? What is the cumulative mortality = passage mortality additive with other causes (Table 2)?
- Is there a need to pass a portion of the population to meet social or cultural goals?
- What is the capacity of the fish pass structure, daily and cumulatively?
- If species are collectively managed as guilds, are there species in the guild most at risk of direct and indirect effects associated with passage? Can one species best represent the guild and therefore become of the target for passage decisions?
- How will changes in species numbers up- or downstream impact the broader ecosystem, e.g., food web impacts or via altered competition among species?

To answer the questions, each species (or guild or its representative species) requires an assessment table in preparation for the comprehensive analysis. The assessment table can be simple (Table 2) or complex, e.g., incorporating life history strategies, single vs. multiple spawning grounds, etc. Table 2 is a simple hypothetical example of a diadromous species passing three dam and reservoir barriers. It does not show the complexity that could be included, e.g., differences in mortality and efficiency rates that may exists between sexes or among body sizes and sex-differentiated contributions to reproduction. How many of such factors are included depends on the overarching goals, existing biological knowledge for the river's population, and the state of population dynamics modelling which may be simple (Table 2), coarse scaled, e.g., "sea run fish habitat" (Roy et al. 2018), or multifaceted and very complex (e.g., Gibson and Meyers 2003; Barber et al. 2018; Stich et al. 2019; Song et al. 2020). Once completed, Part 2 answers are assembled as a decision matrix based on the best estimates of the biological outcomes of passage for each species or guild at each barrier and cumulatively. Uncertainty will accompany these models (Patterson et al. 2001; Saltelli 2002), and any uncertainty should be clearly documented (e.g., Wegscheider et al. 2021). Parts 1 and 2 set the stage for decision-makers to assess scenarios about species and proportions passing, i.e., the best available science and knowledge will be in hand to begin the structured decision-making for designing a fish passage plan (Part 3).

Part 3: Structured decision-making

Answering the questions in Part 1 and 2 will not generate an effective fish passage solution for a system because (1) it is rare that sufficient historical and contemporary data is available to fully answer the questions; (2) there is always uncertainty in estimates; and (3) there will always be competing management objectives in addition to fish passage for the system. To assist in evaluating different management options, our framework advocates for the use of structured decision-making (SDM—Part 3, Fig. 1). SDM is a strategic and adaptive process that can assist decision-makers in evaluating the consequences of management scenarios in the presence of uncertainty and competing objectives or values. Excellent introductions to SDM are provided by Peterman and Peters (1998), Irwin et al. (2011), and Gregory et al. (2012).

SDM has been used successfully in fisheries science and management to aid in complex decisions such as defining fisheries allocations (Bernstein and Iudicello 2002; Varkey et al. 2016) and to assess alternative management options related to fish passage (Mossop and Higgins 2012; McLaughlin et al. 2013). There are various approaches and tools used in SDM, but the general process consists of engaging rightsholders and stakeholders (participatory approach), defining and evaluating management options and objectives, and using a modeling approach to incorporate uncertainty and predict the outcome of different management options on the stated objectives (Peterman and Peters 1998; McLaughlin et al. 2013). SDM analysis tools are numerous and include Bayesian belief network analysis, decision analysis, and real-options analysis, which approach to choose will vary among practitioners (Gregory et al. 2012). The structure and process should follow these basic steps (after Peterman and Peters 1998):

a) Define the system-wide fish management goals (objectives/targets).
b) Define passage options for each species/guild (herein Parts 1 and 2).
c) Identify and estimate uncertainty with each passage option (Parts 1 and 2).
d) Model the outcomes of options including the uncertainty associated with each option (Part 2).
e) Estimate the costs or feasibility of each option entering into the decision tree, e.g., a $100 M fish ladder versus $10 M fish trap and transport option, sustaining spillway flows for a downstream migration (may not be possible for some structures) etc.
f) Build a decision-tree or decision-table based on model output (Parts 1 and 2).
g) Weigh and rank the management options based on the decision tree/table (Parts 1 and 2).
h) Perform a sensitivity analysis for the decision tree/table to determine parameters driving the decision outcomes.

It will be apparent that the SDM process is complicated (modelling Parts 1 and 2) and requires sufficient time to complete (assembling and scheduling the process among regulators, operators, the science support team, rightsholders, and stakeholders). Other decision-making models exist and may be equally useful depending on the management situation, e.g., system dynamics modeling (Song et al. 2021), multi-objectives genetic algorithm (Roy et al. 2018), and optimization modelling (Kuby et al. 2005).

Conclusions

Comprehensive watershed management is a complex decision-making and planning process where success depends on solid foundations about the state

Table 2 A simple example of a species or guild passage assessment table for a river with three barriers. (A) Represents the assessment model for migrants moving upstream, e.g., adults migrating to their spawning grounds, and (B) is the downstream movements by out-migrating individuals returning down river, e.g., juveniles. The simple example shows rates (proportions) attributed to each of the challenges presented by passage structures, i.e., the fishway and reservoir

Barrier	Direction	Challenge	Efficiency[1] (rate)	Natural mortality[2] (rate)	Harvest[3] (rate)	Total mortality[4] (rate)	Cumulative mortality (rate)	Example[5] "1,000" Upstream and "100,000" Downstream
(A) Migrants moving upstream								
Barrier 1	Upstream	Fishway	0.95	0.05	0.01	0.11	0.11	890
Barrier 1	Upstream	Reservoir	0.95	0.10	0.00	0.15	0.24	757
Barrier 2	Upstream	Fishway	0.95	0.05	0.01	0.11	0.33	673
Barrier 2	Upstream	Reservoir	0.95	0.10	0.00	0.15	0.43	572
Barrier 3	Upstream	Fishway	0.95	0.05	0.01	0.11	0.49	509[6]
(B) Migrants moving downstream								
Barrier 3	Downstream	Fishway	0.95	0.08	0.00	0.13	0.13	87,500
Barrier 2	Downstream	Reservoir	0.95	0.08	0.00	0.13	0.23	76,563
Barrier 2	Downstream	Fishway	0.95	0.08	0.00	0.13	0.33	66,992
Barrier 1	Downstream	Reservoir	0.95	0.08	0.00	0.13	0.41	58,618
Barrier 1	Downstream	Fishway	0.95	0.08	0.00	0.13	0.49	51,291 [7]

[1] Efficiency = either known or estimated efficiency of the fishway and passage through the reservoir

[2] Natural mortality = either the known or estimated natural mortality arising from the fishway, i.e., post-passage, residual mortality rate (indirect mortality of passage) and passage through the reservoir

[3] Harvest mortality = any known mortality due to commercial, recreational, indigenous, or illegal harvesting of the species

[4] Total mortality = total mortality associated with either the fishway or reservoir. Note that other removals must be incorporated into this total mortality, e.g., removal of mature individuals for supplementation programmes (hatcheries)

[5] Examples of the cumulative effects of passage based on (A) migrants (e.g., adults) arriving at the first fishway in a system (1,000 individuals) and (B) total number of juveniles migrating from the spawning grounds (100,000 individuals)

[6] The total number of migrants that reach the spawning grounds

[7] The total number of out-migrating individuals that survive the fish passage structures in the river system

of the environment (Heathcote 2009; Gregory et al. 2012). We have presented a fish passage decision-making framework which will provide that solid, science-based foundation. It addresses the biologically relevant information required to set the stage for decision-making, generating a comprehensive matrix of the science knowledge among passage choices and their predicted outcomes from which managers can take forward in their broader, comprehensive river-wide decision-making process. The guiding questions of Parts 1 and 2 will help decision-makers understand when passage is appropriate and necessary for a species (or fish group or guild), how many to pass, and when. Part 3 generates a quantitative analysis of the passage options that embraces the uncertainty of unknown biological consequences and promotes the inclusion of differing views from rightsholders, stakeholders, regulators, and operators. Key caveats in the framework are that each system: (1) will be ecologically different and thus unique in the development of Parts 1 and 2; (2) will have varied states of knowledge and data availability, i.e., degrees of uncertainty; and (3) will be in different states of management and decision-making, e.g., goals and targets for species may exist or not, or be in development. It follows that one pass through the framework is just a first step. Effective management of the river ecosystem in relation to fish passage always requires an adaptive approach whereby mechanisms exist to incorporate new knowledge, information, and opinion into a fluid and punctuated, decision-making process. Successful fish passage decision-making must incorporate a multi-species, ecosystem focus that is participatory and transparent, embraces uncertainty, and takes an adaptive approach; consequently, it will take time which requires patience. We have presented a decision-making framework that can achieve effective and therefore successful fish passage solutions, but we also recognize this approach advocates for a paradigm shift in fish passage decision-making and management. Cracks in the old paradigm are emerging (e.g., Poff and Olden, Torgersen et al. 2022; Curry et al. 2020), so it is imperative that operators, regulators, rightsholders, stakeholders, and science keep working together to build this new paradigm that embraces a whole ecosystem approach.

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Declarations

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