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A new framework for assessing roughness elements in promoting fish passage at low-head instream structures

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ABSTRACT

Increasing interest in fish passage solutions past low-head instream structures has led to the development and implementation of new designs with various types of roughness elements within these structures. We know that roughness elements increase the heterogeneity in water velocity by creating a continuous or discrete low velocity zone, which supports fish passage. However, the effectiveness of these roughness elements for various low-head structures and fish species differs and is often not assessed in detail. This paper highlights three important aspects of assessing roughness elements, namely fish behavior, flow hydrodynamics and passage efficiency. A novel multi-stage framework that can be used for assessing the effectiveness of fish passage solutions is proposed. Initially, we consider the uniqueness of behaviour between species and the hydrodynamics created by roughness elements, as a generalized solution for the size and arrangement of these elements might not work effectively for all species. Then, for effective performance, the link that is required between fish behaviour (both individual and for groups) and hydrodynamics and effectiveness of the roughness elements is discussed for ensuring effective use in low-head structure designs. The proposed framework synthesizes the information required for effective solutions to fish passage through low-head structures.

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Introduction

Disruption of river connectivity due to various types of instream structures has contributed to the population decline of many fish species throughout the world (Birnie-Gauvin et al. 2019). The desire to restore river connectivity and fish migration pathways at these structures has resulted in the development of fish passes, also known as fishways. This scientific solution, which dates back to the early twentieth century, relies on the theory of providing additional hydraulic structures to ensure that water velocities and depths are matched with the requirements of a target fish (Katopodis and Williams 2012). Various types of fish passage solutions have been designed and tested with fish found commonly in northern temperate regions, such as salmonids, and have then been transferred to other parts of the world (Kemp 2016). Most of these standard solutions have been designed to overcome impediments to migration at large barriers, but their use at low-head structures are limited due to space and economic constraints. Although the distinction between large and low-head structures has not been well defined, the term 'low-head structures' usually applies to those such as culverts, small weirs, fords or causeways and tide gates (Franklin et al. 2018; Birnie-Gauvin et al. 2019). Some of these structures are built to facilitate connection along the river when additional infrastructure is added, such as road crossings, whilst others facilitate water discharge guidance or measurement. Typically, more attention has been given to larger scale structures, due to physical size, socio-economic cost, trans-boundary issues, political and strategic importance and the extent of impact. In contrast, the solutions for fish passage at low-head structures are often generalized and provided in the form of guidelines specific to design and construction of such structures, e.g., New Zealand Transport Agency (2013).

Assessment of low-head structures has shown their negative impacts on fish migration to be similar to those of large ones, especially when the effects are considered cumulatively (Warren Jr and Pardew 1998; Gibson et al. 2005; Januchowski-Hartley et al. 2013). For example, a recent study from New Zealand has shown a significant effect of these small structures on river connectivity, with almost 12 percent of the New Zealand river network (based on an incomplete census of structures) being hindered by culverts (Franklin and Gee 2019). This has increased

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the interest of environmentalists and biologists to better understand the effect of these low-head structures (Kapitzke 2007; Bouska and Paukert 2010; Amaral et al. 2016; Branco et al. 2017) and has pushed engineers to consider ecological requirements in addition to specific hydraulic requirements while planning new structures. It has also generated interest in developing effective retrofitting techniques to enhance the fish passage efficiency of existing structures (Leng and Chanson 2019). However, designing structures with two dichotomic requirements, one being fish passage and the other being able to handle discharge, including sediment, within economic constraints, is always a challenge. This leads to engineers using the well-known concept of increasing hydraulic roughness within the wetted surface of a structure, an idea that has now widely been used in culverts (Ead et al. 2002) and ramps (Baker and Boubée 2006; Baki et al. 2015). The principle behind this concept is based on the assumption that a heterogeneous flow field is generated within the structure/fishway that will enable fish to use low-velocity zones as a resting area (Baker and Votapka 1990; Johnson et al. 2012). Engineering designs of various shapes, forms and arrangements have been developed and used within fishways of different shape, size and length (Muraoka et al. 2017; Rodgers et al. 2017; Goodrich et al. 2018; Wang and Chanson 2018; Amaral et al. 2019; Johnson et al. 2019). A few unique solutions, such as using mussel spat ropes as a form of baffling, have also been developed and tested for different species (David et al. 2014).

The earlier efforts to understand the performance of such roughness elements were focused on their application to culverts and were skewed towards quantifying hydraulic characteristics, rather than fish passage efficiency. Empirical relationships between various hydraulic parameters were established for a culvert with different roughness types and designs (Rajaratnam et al. 1988, 1989, 1990, 1991; Rajaratnam and Katopodis 1990). This was further analysed by Ead et al. (2002) to provide a limited range of relative height and spacing of the roughness element expressed in terms of culvert diameter. These empirical relations and design ranges provided a sound basis for validation of numerical analysis and design for further study (MacDonald and Davies 2007; Feurich et al. 2011; Vowles et al. 2019). Apart from conventional designs, various customized roughness elements, such as sloping baffles (Newbold et al. 2014), ventilated corner baffles (Cabonce et al. 2018; Sailema et al. 2019), longitudinal square beams (Watson et al. 2018) and other industrial designs (Baker and Boubée 2006) have also been developed and tested. However, the study of passage efficiency of fishways with different roughness elements results in various observations. Although the use of these roughness elements is beneficial for various species, it is also observed that for some benthic species, such as river lamprey, the inclusion of roughness elements leads to species abandoning their passage once they come in contact with baffles (Vowles et al. 2019). Similarly roughness elements of the same size and shape have been found to perform differently when the way they are arranged changes (Enders et al. 2017). Furthermore, passage efficiency for a single species has been found to vary between roughness elements of different types (Franklin and Bartels 2012; Amtstaetter et al. 2017).

Objective

The observed wide-spread variation in efficiency for different roughness elements and fish species highlights the need for a more rigorous performance assessment when it comes to roughness suitability for promoting fish passage. Here, a new framework for performance assessment and evaluation of roughness elements for low-head structures is outlined and discussed. The framework is based on the concept of probability for quantifying fish responses to various flow fields. We provide a literature review in which the framework requirements are founded. Based on the requirements, a novel multi-stage framework is proposed that provides valuable guidance for low-head structure design. As a result it is expected that implementation of the performance assessment will improve the passage of targeted species under varying hydrological and hydraulic condition (Katopodis et al. 2001). The assessment framework considers both the proportion of fish that successfully pass hydraulic structures and extracts the information on altered flow fields and fish location. Results from many previous studies focus on either hydrodynamic (Shamloo et al. 2001; Sadeque et al. 2009; Lacey and Rennie 2012) or behavioural (Liao et al. 2003b; Tritico and Cotel 2010; Link et al. 2017) observations for a single roughness element, but synthesising hydrodynamic assessment with fish behavioural analysis is important for effective fish passage design.

Linking roughness hydrodynamics with passage efficiency

Passage efficiency, being one of the most crucial aspects of fish passage solutions, is presently the most widely discussed topic in fish passage research (Noonan et al. 2012; Silva et al. 2018). However, most of the evaluation of these structures are biased

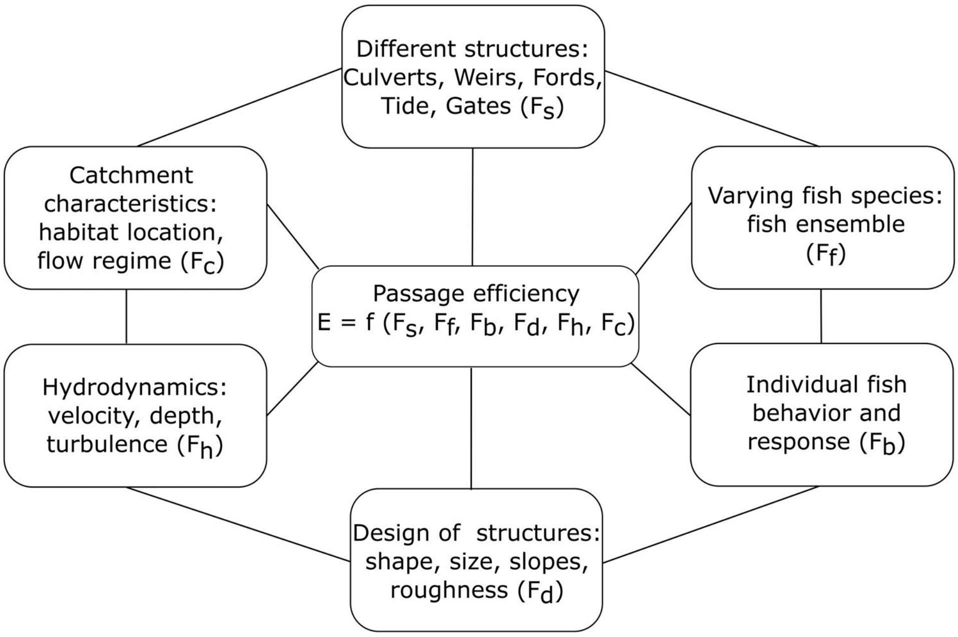

Figure 1. Processes that govern the effectiveness of individual fish passage at various scales.

towards standard fish passage designs and target species (Mallen-Cooper and Brand 2007; Bunt et al. 2012; Noonan et al. 2012). Although the idea of improving fish passage solutions through low-head structures mimics the principles of standard fishways, there are a number of designs that function differently, especially those that are based on providing an additional roughness element. These roughness elements, based on their shape, form and arrangement, generate various flow fields, which in turn interact with fish swimming ability to determine the passage efficiency (Santos et al. 2014; Muraoka et al. 2017). For example, longitudinal baffles (Watson et al. 2018), surface roughening (Rodgers et al. 2017; Goodrich et al. 2018) and other non-conventional designs such as mussel spat rope (Tonkin et al. 2012; David et al. 2014) will produce a flow field with connected low velocity zones. This results in a continuous pathway for small-bodied swimming species. Whereas discrete roughness elements, such as weirs and baffles, will produce discontinuous low velocity zones around single elements. This will require fish to travel through high velocity zones to access these refuge areas. For such design, each baffle has to be arranged to ensure the location of low velocity zones within the burst swimming distance of targeted fish species (Katopodis et al. 2001). In addition, for some cases, such as for weir baffles, the nature of the flow changes from skimming to plunging. This requires fish to jump over these weirs, benefiting jumpers whilst restricting swimmers (Baker 2003). These examples highlight the important role that hydrodynamics and behaviour of individual fish play in the overall effectiveness of fish passage solutions through low-head instream structures. Depending on fish behaviour and their preference for certain hydraulic conditions, particular designs may be effective for some species but not for others.

Similar to standard fishways, the passage efficiency through these low-head structures can further be related to multiple factors (Figure 1). Overall, these factors can be broadly classified into two categories: (i) one that determines efficiency at the individual structure scale and (ii) one that determines efficiency at the catchment scale. The ideal structure, as conceptualized by Castro-Santos et al. (2009), would be one that performs well at both scales. Such a structure should allow a high proportion of fish to pass, without significant post passage effects. However, there is very limited research on the field assessment of low-head structures that allows us to evaluate performance at both scales. One exception is the study by Franklin and Bartels (2012), where the upstream passage of *Galaxias maculatus* was studied after retrofitting 73.8 m of culvert. Temporal data on upstream fish communities, in addition to an evaluation of passage performance for a single species, has made it possible to evaluate effectiveness at both individual structure and catchment scales. A diversity in species found can also be an indicator of performance improvement, by identifying a significant increase in new species upstream of the structure immediately after the remediation. However, at an individual structure scale, a relatively low passage efficiency for the target species highlights the necessity to better understand their behaviour, their preference for particular flow conditions, and their response to flow fields developed from individual roughness elements under the varying flow conditions, size and shape of the roughness element.

Table 1. Overview of studies performed to understand fish behaviour in turbulent flow condition using different turbulent generators.

	Species/ taxa tested	Body length (cm)	Turbulent generator
Webb (1998)	*Nocomis micropogon*	~10.6	Vertically and horizontally oriented cylinders of
	Micropterus dolomieu	~8	0.64, 1.3, 1.9, 2.5 cm diameter
Liao et al. (2003b)	*Oncorhynchus mykiss*	10.0 ± 0.3	D shaped cylinder of 2.5 and 5 cm diameter.
Nikora et al. (2003)	*Galaxias maculatus*	L_1: 4.8 ± 0.25	Corrugated walls
		L_2: 6.22 ± 0.65	
		L_3: 9.18 ± 0.1	
Lupandin (2005)	*Perca fluviatilis*	L_1: 4.42 ± 0.41	Turbulent property of the flow controlled by special device.
		L_2: 7.60 ± 0.52	
		L_3: 10.42 ± 1.01	
Smith et al. (2005)	*Oncorhynchus mykiss*	L_1: 9.01 ± 0.16	Prismatoidal shape formed by bricks
		L_2: 4.42 ± 0.12	($L \times B \times H$: $22.6 \times 11.3 \times 3.0$ cm)
Liao (2006)	*Oncorhynchus mykiss*	16.6 ± 0.4	D-Shaped cylinder of 5 cm diameter
Przybilla et al. (2010)	*Oncorhynchus mykiss*	14.1 ± 2.1	D- shaped vertical cylinder of 5 cm dia.
			Semi-infinite flat plate of length ($L \times H$: 35×40 cm)
Tritico and Cotel (2010)	*Semotilus atromaculatus*	12.2 ± 0.9	Cylinders of 0.4, 1.6 and 8.9 cm diameter
Goettel et al. (2015)	*Rhinichthys obtusus*	6.5 ± 0.6	Turbulence created by bricks of dimension
			($L \times B \times H$: $20 \times 10 \times 5.5$ cm)
Maia et al. (2015)	*Leopmis macrochirus*	13.3 ± 1	Rotating turbine of 6 cm diameter
Link et al. (2017)	*Cheirodon galusdae*	4.48 ± 0.15	Vertical cylinders:
	Basilichthys microlepidotous	7.77 ± 0.59 cm	Diameter: 2,3,4,5 and 6 cm
Muhawenimana et al. (2019)	*Oreochromis niloticus*	11.78 ± 2.11 cm	Horizontal cylinder of 5 cm diameter

L: length, B: width, H: height

Similarly, other types and sizes of baffles have also been field tested, particularly for galaxiidae species. Although these studies showed a significant increase in their passage rate, their suitability at catchment scale could not be evaluated due to a lack of information on performance of other species within the same catchment (MacDonald and Davies 2007; Amtstaetter et al. 2017). Although the analysis at both scales is crucial and it is ideal to collect data at both an individual structure scale and catchment scale, with limited monitoring resources this is not always realistic. In situations where detailed field assessments are not possible, thorough laboratory studies can help to assess if a roughness element is fit for purpose (Olsen and Tullis 2013; Newbold et al. 2014). Laboratory investigations should be structured to determine the hydrodynamics of individual roughness elements of different sizes and forms relative to the ability of fish to detect and access the suitable flow fields around those elements. Such interlinks can be established by extending the study within all three dimensions of fish passage hydrodynamics; roughness hydrodynamics, fish behaviour and sensory mechanisms. Here we only concentrate on the interlink between roughness hydrodynamics and fish behaviour.

Overarching behavioural study for passage assessment

In recent years, there has been an increasing number of studies focusing on the behavioural analysis of fish with implication for understanding habitat requirements and passage improvement. These studies have established a benchmark in understanding the behaviour of fish in terms of their kinematics, biomechanics, station holding and energetics in turbulent flow (Nikora et al. 2003; Liao et al. 2003a, 2003b; Lupandin 2005; Liao 2006, 2007; Tritico and Cotel 2010; Webb and Cotel 2010; Maia et al. 2015; Link et al. 2017; Muhawenimana et al. 2019). Although these studies provided crucial information on the hydraulic preferences of different fish species, including their choice of location for different behaviours such as station holding, flow refuging and position for feeding (Smith et al. 2005; Przybilla et al. 2010), the use of this information while assessing the suitability of roughness elements has to be done with care. This is mainly due to most of these studies, as shown in Table 1, using turbulence generators that vary distinctly in shape, size and performance with the ones typically used as roughness elements for facilitating fish passage. Steady and uniform turbulent conditions generated in the laboratory under controlled conditions and using different turbulent generators will differ from those created by the roughness elements used for fish passage listed in Table 2. However, in some cases a close resemblance between the results obtained from behavioural testing and passage efficiency tests were noted, especially when both tests were done either with similar species or with structures producing similar turbulent features. During a passage efficiency test with weir baffles, Khodier and Tullis (2014) noted that wild brown trout (*Salmo trutta*) preferred two distinct zones, one immediately downstream of the baffle and another at the side. Such distinct station holding behaviour at the side of cylindrical obstacles was also seen during the behavioural test of rainbow trout (*Oncorhynchus mykiss*) (Przybilla et al. 2010). Similarly, Enders et al. (2017) related the higher attraction of Alewife (*Alosa pseudoharengus*) and Brook trout (*Salvelinus fontinalis*) towards vertically orientated baffles, with their preference for vertical eddies.

Table 2. Overview of assessment of fish passage through small-scale structures with different roughness elements in laboratory setups.

Paper	Species/ taxa tested	Hydraulic structures	Roughness elements
MacDonald and Davies (2007)	*Galaxias maculatus* *Galaxias truttaceus*	Culvert (L × Ø) 5.5 × 1.5 m	Spoiler baffles (L × B ×H): 100 × 70 × 56 mm 100 × 70 × 28 mm
Franklin and Bartels (2012)	*Galaxias maculatus*	Culvert (L × Ø) 73.8 × 1.5 m	`Spoiler baffles (L × B ×H): 250 × 100 × 120 mm
Olsen and Tullis (2013)	*Salmo trutta*	Culvert (L × Ø) 18 × 0.61 m	Corner & Weir baffles
Khodier and Tullis (2014)	*Salmo trutta*	Culvert (L × Ø) 18.3 × 0.60 m	Weir baffles (H × Y)
Newbold et al. (2014)	*Anguilla anguilla*	Culvert (L × Ø) 6 × 1.2 m	Sloping corner baffles (L × B × H × Y) (350 × 870 × 150 × 1000 mm)
Enders et al. (2017)	*Alosa pseudoharengus* *Salvelinus fontinalis*	Culvert (L × B ×H) 18 × 0.8 × 0. 8 m	Quarter of a cylinder with a radius 0.09 m placed vertically at the wall or horizontally at bed.
Amtstaetter et al. (2017)	*Galaxias species*	Culvert (L × Ø) 70 × 1.5 m	Metal sheet: Covering 25 % of culvert (bottom centre to half way up) on one side.
Cabonce et al. (2018)	*Bidyanus bidyanus*	Horizontal flumes (L × B) 12 × 0.5 m	Triangular corner baffle (H) 0.133 m with and without hole
Vowles et al. (2019)	*Lampetra fluviatilis*	Culvert (L × Ø) 6 × 1.2 m	Spoiler baffles (L × B ×H) 250 × 100 × 100 mm
Baker and Boubée (2006)	*Galaxias maculatus* *Gobiomorphus huttoni*	Artificial fish ramp (W: 20 cm)	Gravel, Cordrain®, Sand, Miradrain® and Brush
Tonkin et al. (2012)	*Gobiomorphus huttoni*	Laboratory culvert (L: 3m and 6m, Ø: 0.35 m)	Mussel spat rope

L: length, B: width, H: height, Y: spacing along the streamwise direction, Ø: diameter

Such preference for specific eddy orientation was also noted in behavioural analysis of other species having similar body morphology (Tritico and Cotel 2010).

These comparable results between trials from two different domains point towards justifying that behavioural information can play a pivotal role in assessing the effectiveness of roughness elements. Of importance is that behavioural information is obtained for the species found within the same catchment and by using obstacles in the laboratory that resemble closely the ones found in the field. One way of extracting such overarching information is to carry out both these trials within the same framework, by using an element that can be transferred into real-world application without significant modification. Additionally, the behavioural information obtained from such studies can also provide information to improve the design of existing roughness elements. For some small bodied rheophilic fish species, the hydrodynamics behind the corner baffles were found to have a negative impact on their passage performance (Cabonce et al. 2018; Sailema et al. 2019). Those fish were found to be oriented towards the main flow direction due to flow reversal in the recirculation zone. This adverse effect was corrected by providing an opening within the baffle, which was found to be effective in minimizing the magnitude of such reversal, ultimately improving the passage efficiency.

Quantifying response from assessment

Although there has been much discussion on the importance of understanding fish behaviour for improving fish passage efficiency, one question that arises is how to quantify such behavioural knowledge so that it can be synthesized to extract the information required for design. There is a need for quantification to be standardized, allowing comparison of behaviour for different species or the same species at different life stages. Previous research quantifying such behaviour evaluates the swimming performance of fish in minimally turbulent conditions, whereas we know that the flow inherent to most fish passage solutions is turbulent in nature (Kemp 2012). This will require a new approach of quantifying fish exposure towards different hydraulic zones. In our framework, such an approach has been proposed to quantify fish behaviour with four main objectives. Firstly, such behavioural quantification should be able to show the ability of fish to find and use suitable flow characteristics. Secondly, quantification should provide an understanding about various ranges of preferred flow parameters that act as a baseline for roughness designs. Thirdly, a tool is required to compare response behaviour within and between fish species. Finally, such quantification should relate the effectiveness of any roughness arrangement with fish behaviour at any time within the hydrological regime. For this purpose, a simple probabilistic distribution curve has been hypothesized that we expect will provide information about the likelihood of fish preferring any particular type of flow fields. Such flow fields can be velocities or different metrics of turbulence, representing intensity, periodicity, orientation and scale (Lacey et al. 2012).

We justify the approach of generating probabilistic behavioural curves by knowing that fish will spend more time station holding or flow refuging at

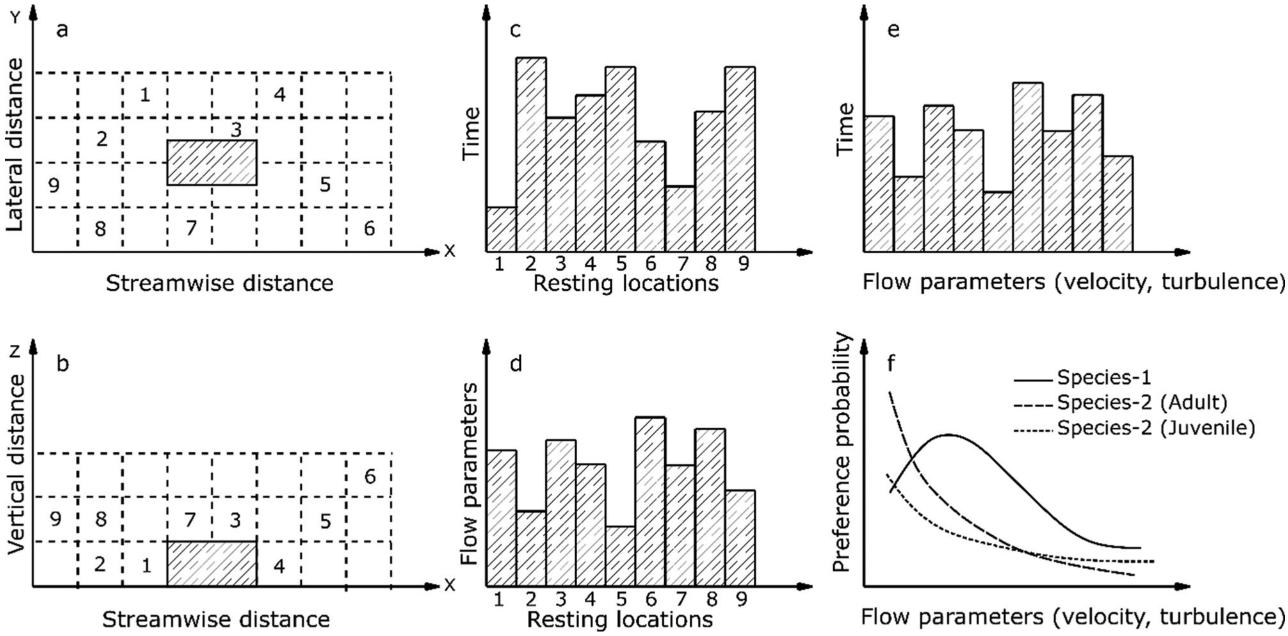

Figure 2. Summary of steps for quantifying fish likelihood for different flow fields, (a, b) is the 3-D hydrodynamic characterization of the flow around the roughness elements, (c) shows the time spent by fish at preferred locations as represented by numbers, (d) is the flow parameter value at those locations, this can be different velocity and turbulent components, (e) is the time spent within certain flow types and (f) is the likelihood (expressed as probability) of fish to prefer certain flow conditions.

a place where hydrodynamic conditions are favourable (Shi et al. 2019). Favourable hydrodynamic conditions can be expressed in terms of energy savings or dynamic postural stability. Hydrodynamic characteristics and the total time spent by individual fish at these locations can be grouped to generate the likelihood of fish response to particular flow conditions. Such a response likelihood for different fish species, or fish at different life stages, can then be expressed in the form of a probabilistic curve. However, one of the limitations of such an assumption is its inability to determine the behaviour regulated by factors other than hydrodynamics, such as the influence of conspecifics, chemical cues and other motivational factors. Although some advanced probabilistic models have already been proposed to study animal motion under such conditions (Capello et al. 2011; Harpaz et al. 2017; Bod'ová et al. 2018), no simple tool that can be generated by tracking fish under different hydrodynamic conditions is currently available. Knowledge of a wide spectrum of flow fields is required to isolate the preference of some flow fields over others. This can be done by generating heterogeneous hydrodynamic conditions by using any obstacles (Shamloo et al. 2001) or individual roughness elements that are generally being used for fish passage solutions, such as baffles (Lacey and Rennie 2012). More complex flow through these objects can be generated by using different geometries and flow conditions (Larousse et al. 1991; Sadeque et al. 2008). An example for the generation of such behavioural curves, including the expected nature of curves for different fish species, is shown in Figure 2. Accordingly, as shown in Figure 2(a, b), the specific location of fish in a flow field generated by a baffle can be traced in all three spatial dimensions using image analysis. The numbers (1 to 9) represent the location of fish at different times. Figure 2(c, d) show the time spent by fish and the magnitude of flow parameters within those locations, respectively. Commonly assessed flow parameters are time-averaged velocities or turbulence characteristics (Silva et al. 2011). This information can then be combined to generate the information on fish preference in relation to flow parameters (Figure 2(e)), which in turn facilitates the calculation of fish preference probability for either station holding or flow refuging (Figure 2(f)).

Hydrodynamic quantification of any heterogeneous flow can be obtained by various measurement tools and methods. Acoustic and image-based measurements are two of the commonly used methods to characterise flow fields for fish behaviour studies (Knapp et al. 2019). In addition, lateral line probe (LLP) assessment (Fuentes-Pérez et al. 2015, 2018) and numerical simulations (Quaresma et al. 2018; Amaral et al. 2019), such as computational fluid dynamics (CFD) have been adopted in some recent studies. Similarly, various swimming kinematics of fish and motion tracking information can be used, and quantified with image analysis (Qian and Chen 2017). As a result, the preferred fish location for station holding or sustained swimming can be determined. The hydrodynamic properties and the total time spent in these locations can then be used for a probabilistic quantification of response to particular flow conditions. Although probabilistic quantification

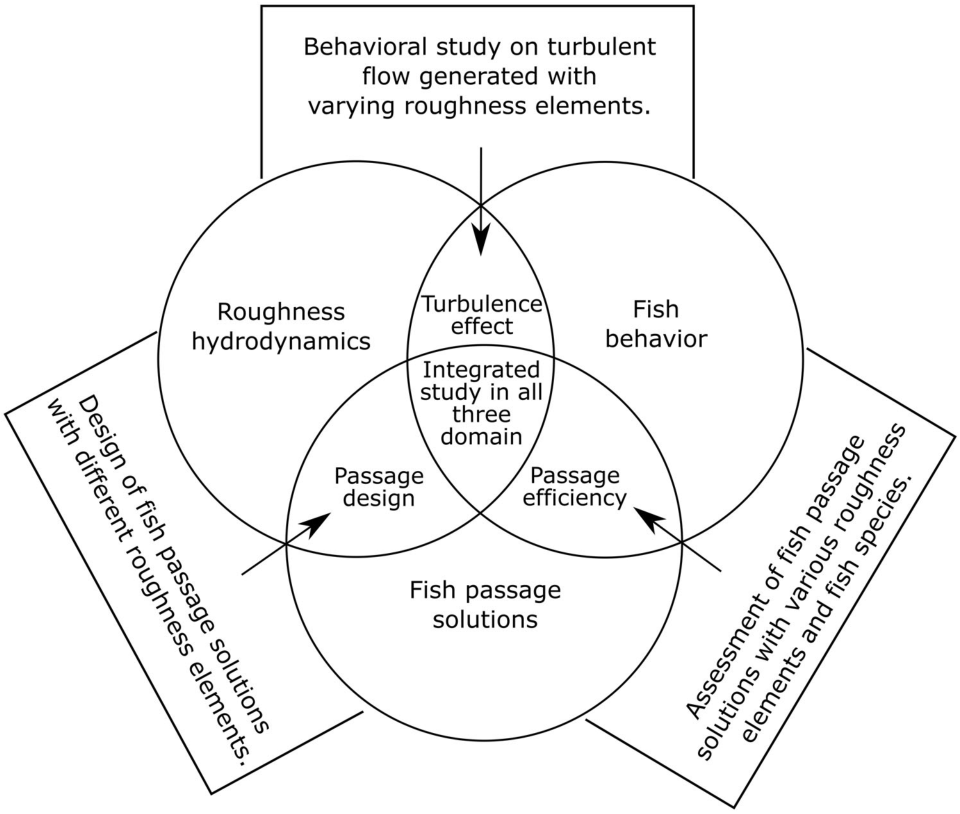

Figure 3. Current research scenario in low-head fish passage solutions within three different domains and the framework requirement to integrate the information within all these domains.

of fish behaviour has been done before (Capello et al. 2011; Vowles et al. 2014; Shen et al. 2016), such quantification was based on non-hydrodynamic variables. Using hydrodynamic conditions, we expect that characterizing fish behaviour in terms of flow variables will provide valuable information for fish passage design. Comparison of behavioural curves is expected to provide crucial information on the ability to detect different flow variables and the range of those variables preferred by fish for resting and movement. One such case can be the effect of water velocity and turbulence on fish swimming ability. Fish, such as juvenile rainbow trout, as observed by Smith et al. (2005), can have a skewed Gaussian type of relationship with velocity. For this case, fish show their preference for more turbulence, whereas for other fish an exponentially decaying type of relationship with turbulence can be displayed, preferring lower turbulence (Hockley et al. 2014). The work can be further extended to observe the variation in behavioural curves with different motivating conditions, such as migration, feeding, refuge and presence of predators.

From behaviour study to passage assessment: integrated framework

Although there has been an increasing number of independent studies on fish behaviour, passage efficiency and roughness hydrodynamics, studies covering all three aspects of fish passage science within the same framework have been limited so far. Since the effectiveness of a roughness element is inter-related with its hydrodynamics and fish behaviour, studies performed independently within a single domain might not be effective enough to provide information required for the other domain. Figure 3 shows the interlink between various sectors involved in the context of the current research and the requirement for an integrated approach to develop an effective fish passage solution. In this regard, we propose a novel multi-stage framework whereby all these studies are interlinked, with an ultimate objective of extracting information that is crucial for planning effective roughness elements. The framework has been designed using spoiler baffles as an example. Spoiler baffles are one of the most widely used roughness elements in culverts, but are also used for assessing other types of wall roughness. The conceptual layout of the overall framework is shown in Figure 4. It consists of three stages, each stage supplementing the information required for the next.

Elementary stage: Understanding behaviour around a single roughness element

The first stage is the elementary stage, where the effects on a single baffle are studied and assessed. These effects include hydrodynamic changes, and changes in fish behaviour for altered conditions. Information about the relationship between the geometry of the baffle, the hydraulic characteristics of approach flow and the

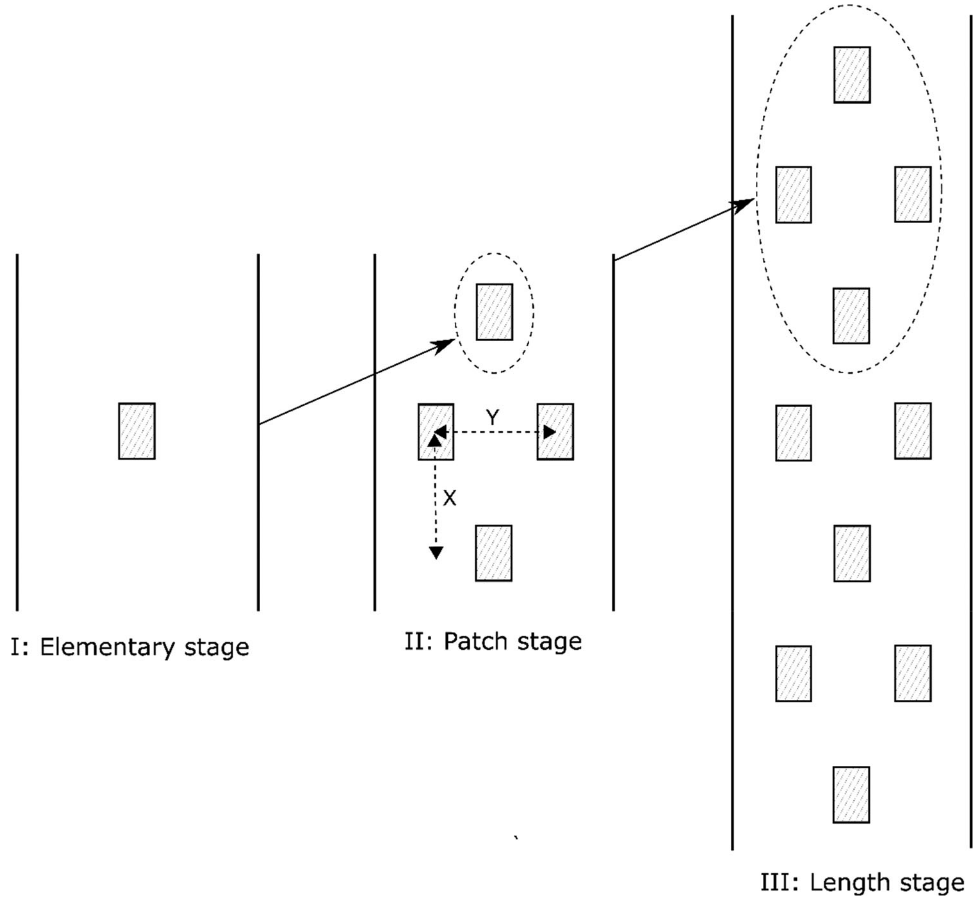

Figure 4. Schematic representation of different research stages within the framework, using spoiler baffles (Y and X: lateral and longitudinal spacing from centre of the baffle).

hydrodynamic alteration from the baffle are assessed here. Such relationships can be obtained by studying the baffle as a 2D or 3D flow obstacle. For example, the extent of low velocity zones and turbulence around the baffle can be quantified, and correlated with variations in the roughness elements' dimensions, (i.e., shape, length and aspect ratio) (Martinuzzi and Tropea 1993). The analysis can further be extended to determine the effect of variation in approach flow conditions, such as water velocity and depth (Larousse et al. 1991; Shamloo et al. 2001; Sadeque et al. 2008, 2009). This is followed by studying the response of fish toward the altered flow in the presence of the baffle, including determining the preferred location for station holding or flow refuging and understanding the hydrodynamic characteristics of preferred locations. These tests should be repeated for different species or at different life stages within the same species. The size and shape of the baffle can be then optimized for design considerations and studies can progress to the second stage of the framework.

Patch stage: Information for design

The second stage consists of the patch stage, where a certain number of baffles with specific dimensions, as determined during the first stage, can be grouped together to create a patch. These patches have to be designed in a way that they can be scaled to the full dimensions of a low-head instream structure. The important design feature of these patches are the longitudinal and lateral spacings for individual baffles. In some design guidelines, the recommended dimensions and spacings of baffles are based on the numerical simulation of the low velocity zones downstream of each set of baffles (Stevenson and Baker 2009). Although the extent of the low velocity zone is a crucial factor for the selection and arrangement of baffles, the pathway hydrodynamics used by fish for traversing from one low velocity zone to another also needs to be considered. So far, fish behaviour studies mostly assess the effect of turbulence and limited attention has been given to the pathway hydrodynamics (Goettel et al. 2015). In this seminal study Goettel et al. (2015) found that the pathway chosen by blacknose dace (*Rhinichthys obtusus*) had similar turbulence magnitudes, as assessed with turbulence kinetic energy and Reynolds shear stresses. It is important for such information to be also extracted for other fish species. Designs need to allow for continuous path creation, likely to be preferred by the target species.

Length stage: Final evaluation

The third and final stage is the length stage, where the patches tested during the second stage are scaled up to the whole length of the desired low-head instream structure. Commonly, statistical evaluation of passage performance is the assessment tool at this stage. Most of the laboratory trails on evaluating the efficiency of the roughness elements rely on overall passage performance. This is usually proportional to the number of fish that successfully pass the whole length of the hydraulic structure. However, as shown by Castro-Santos and Perry (2012), this metric lacks in providing information on factors that affect the overall passage process. We advocate for using time to event analysis, which considers events corresponding to various stages of passage, such as approach, attraction, entrance and eventual passage through the structure (Castro-Santos and Perry 2012; Ovidio et al. 2017). Newbold et al. (2014) observed European eel (*Anguilla anguillas*) spending more time in a culvert after installing the roughness elements and related this with time spent by fish resting in the low velocity zone near the roughness elements. Similarly, other design information, such as maximum length and slope need to be studied. To maintain consistency within the framework, each of these studies has to be undertaken by using the same roughness elements and species. The results from all these studies can then be assembled to synthesize the information that is crucial for preparing the detailed design of low-head instream structures with roughness elements.

Discussion

Although we are aware of the effects of anthropogenic management of water resources on fish migration for over a century, the majority of fishway science is still biased towards large-scale structures. However, due to easiness in design, fabrication, installation and operation, the use of these low-head structures is increasing. In recent years, the impacts of low-head structures have gained more attention, especially in the Southern Hemisphere, where a significant number of indigenous small-bodied fish are in decline (Habit et al. 2010; Franklin and Gee 2019). The existence of uniform higher velocity zones within these low-head structures has been highlighted as the main obstruction to efficient fish passage (Baudoin et al. 2015). Consequently, engineering solutions that convey flow, whilst creating pockets of low velocity zones to promote fish passage, are sought. This has led to retrofitting structures with secondary elements, herewith considered as roughness elements, which increase flow resistance. For example, three different studies show that certain roughness elements, namely ring baffles (Amtstaetter et al. 2017), spoiler baffles (MacDonald and Davies 2007) and mussel spat rope (David et al. 2014) show improvement in the upstream passage of inanga (*Galaxias maculatus*). Similarly, for assessing the upstream migration of inanga, the size and arrangement of spoiler baffles used by Franklin and Bartels (2012) differs from that used by MacDonald and Davies (2007), whilst both studies show an improvement in overall passage. Although these different forms of roughness elements have been tested and used globally, a coherent procedure of assessment method on how to choose a particular type is lacking. This leads to confusion for practitioners when it comes to selecting the appropriate type for any particular species.

If performance assessments follow an established procedure, such as in the form of an integrated framework as presented in this paper, integrated hydrodynamic and behavioural needs can be better compared. Using the example of low velocity zones around individual roughness elements, although the concept of fish resting has been a basis for selecting roughness elements fit for retrofitting, very limited behavioural data exist on how fish use these low velocity zones while passing through hydraulic structures (Khodier and Tullis 2014). Whilst a few studies have assessed the resting behaviour of fish in controlled laboratory conditions (Liao et al. 2003b; Przybilla et al. 2010; Tritico and Cotel 2010; Link et al. 2017; Muhawenimana et al. 2019), we know that transferring those behavioural observations to field condition is challenging. For the introduced performance assessment framework, we proposed documenting the probability of resting for particular flow conditions as an appropriate behavioural quantification for resting. This would provide information about a range of flow conditions within which fish are likely to behave a certain way. Once this information is obtained, various geometric aspects of roughness elements can be compared with respect to their ability to produce such a range, not only for single elements, but also at the patch scale.

Previous studies have shown that a properly arranged patch can improve the overall efficiency. The arrangement of roughness elements was critical in observing either an increase in the number of fish passing through structures or a decrease in passage time (Santos et al. 2014; Muraoka et al. 2017). Specific patch arrangements, determined by longitudinal and lateral spacing between individual roughness elements, can either be based on the velocity recovery principle (Acharya et al. 2000) or the maximum fish length required to pass through a structure (Stevenson et al. 2008). With any patch arrangement, it is expected to have either a continuous or distributed low velocity zone, aligned with the swimming capacity of the targeted fish species (Feurich et al. 2012). However, swimming capacity of fish, such as for native New Zealand species, is based on minimal turbulent conditions (Mitchell 1989), whereas flow altered by roughness elements will experience an increased level of turbulence. Thus, an assessment outcome would likely either overestimate the swimming capacity or underestimate the energy expended in turbulent flow condition. To mitigate this, we propose to allow for different turbulent conditions in the hydrodynamic assessment where possible, on which the swimming capacity assessment will be based on. If turbulent conditions cannot be assessed practically, comparison of pathways can be a suitable criteria for assessing different patch-scale arrangements, specifically in conditions where the extent of low velocity zones alone is insufficient for justifying the appropriateness of a particular patch layout (Muraoka et al. 2017). Once the key variables governing the swimming pathways are known, the choice of size and arrangement can be made by comparing the presence of these suitable micro-channels (Acharya et al. 2000).

For practical uptake, providing a limiting range of different geometric characteristics, such as length and slope, is of importance. Where the locational information of passage solutions is known prior to the assessment, other criteria such as resistance to flow, sediment and debris can also be considered. Depending on the catchment characteristics upstream of, and general stream features in, the location of the structure, the multi-stage assessment of the integrated framework can be extended to include operational criteria, such as monitoring and maintenance plan requirements.

Conclusions

Despite the fact that a significant number of studies assessed fish behaviour and the effectiveness of different roughness elements for fish passage, a lack of an overarching framework has made it difficult to extract and manage information required for effective fish passage design. Studies have provided useful information for habitat analysis and design of standard fishways, but their use for low-head structures, especially those designed with roughness elements in mind, is limited. In this paper, we identified the present challenges for effective fish passage solutions and have formulated an integrated approach needed for future study in this field. On that basis, we have proposed a new framework for future research and assessment of fish passage past low-head structures. We took into account hydrodynamics, fish behaviour and the pathway characteristics preferred by fish. We discussed an approach that interlinks the tangible aspect of roughness design with intangible fish behaviour. Under this framework, a series of assessments carried out at different outlined stages will provide information on the suitability of any particular types of roughness elements. Such information can facilitate the design of shape, size and arrangement of roughness elements. A probabilistic approach is proposed to quantify fish behaviour, such that its likelihood towards any particular type of roughness element can be related to the likely hydrodynamic conditions generated by the roughness element. The framework will be tested through a series of experiments performed in laboratory conditions. This will include examining the behaviour of various fish species by using roughness elements of different shapes and sizes. Crucial information for design guidelines will be extracted from those experiments, facilitating the construction and retrofitting of effective low-head fish friendly instream structures.

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References

Acharya M, Kells J, Katopodis C. 2000. Some hydraulic design aspects of nature-like fishways. Building Partnerships. p. 1–10.

Amaral SD, Branco P, da Silva AT, Katopodis C, Viseu T, Ferreira MT, Pinheiro AN, Santos JM. 2016. Upstream passage of potamodromous cyprinids over small weirs: the influence of key-hydraulic parameters. J Ecohydraulics. 1(1–2):79–89.

Amaral SD, Quaresma AL, Branco P, Romão F, Katopodis C, Ferreira MT, Pinheiro AN, Santos J. 2019. Assessment of retrofitted ramped weirs to improve passage of potamodromous fish. Water. 11(12):2441.

Amtstaetter F, O'Connor J, Borg D, Stuart I, Moloney P. 2017. Remediation of upstream passage for migrating Galaxias (Family: Galaxiidae) through a pipe culvert. Fish Manag Ecol. 24(3):186–192.

Baker CF. 2003. Effect of fall height and notch shape on the passage of inanga (*Galaxias maculatus*) and common bullies (*Gobiomorphus cotidianus*) over an experimental weir. N Z J Mar Freshwater Res. 37(2):283–290.

Baker CF, Boubée J. 2006. Upstream passage of inanga *Galaxias maculatus* and redfin bullies *Gobiomorphus huttoni* over artificial ramps. J Fish Biol. 69(3):668–681.

Baker CO, Votapka FE. 1990. Fish passage through culverts. US Department of Transportation, Federal Highway Administration, Report No. FHWA-FL-90-006, Washington, D.C.

Baki ABM, Zhu DZ, Rajaratnam N. 2015. Turbulence characteristics in a rock-ramp-type fish pass. J Hydraul Eng. 141(2):4014075.

Baudoin J-M, Burgun V, Chanseau M, Larinier M, Ovidio M, Sremski W, Steinbach P, Voegtle B. 2015. Assessing the passage of obstacles by fish. Concepts, design and application. Vincennes (France): Onema.

Birnie-Gauvin K, Franklin P, Wilkes M, Aarestrup K. 2019. Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene. Aquatic Conserv: Mar Freshw Ecosyst. 29(7):1095–1105.

Bod'ová K, Mitchell GJ, Harpaz R, Schneidman E, Tkačik G. 2018. Probabilistic models of individual and collective animal behavior. PloS One. 13(3):e0193049.

Bouska WW, Paukert CP. 2010. Road crossing designs and their impact on fish assemblages of Great Plains streams. Trans Am Fish Soc. 139(1):214–222.

Branco P, Amaral SD, Ferreira MT, Santos JM. 2017. Do small barriers affect the movement of freshwater fish by increasing residency? Sci Total Environ. 581:486–494.

Bunt C, Castro-Santos T, Haro A. 2012. Performance of fish passage structures at upstream barriers to migration. River Res Applic. 28(4):457–478.

Cabonce J, Wang H, Chanson H. 2018. Ventilated corner baffles to assist upstream passage of small-bodied fish in box culverts. J Irrig Drain Eng. 144(8):4018020.

Capello M, Soria M, Cotel P, Deneubourg J-L, Dagorn L. 2011. Quantifying the interplay between environmental and social effects on aggregated-fish dynamics. PloS One. 6(12):e28109.

Castro-Santos T, Cotel A, Webb PW. 2009. Fishway evaluations for better bioengineering an integrative approach. In: Challenges for diadromousfishes in a dynamic global environment, Haro AJ, Smith KL, Rulifson RA, Moffit CM, Klauda RJ, Dadswell MJ, Cunjak RA, Cooper JE, Beal KL, Avery TS, editors. Bethesda, MD: American Fisheries Society, Symposium 69. p. 557–575.

Castro-Santos T, Perry RW. 2012. Time-to-event analysis as a framework for quantifying fish passage performance. In Telemetry techniques: a user guide for fisheries research. Bethesda, Maryland: America Fisheries Society. p. 427–452.

David BO, Tonkin JD, Taipeti KW, Hokianga HT. 2014. Learning the ropes: mussel spat ropes improve fish and shrimp passage through culverts. J Appl Ecol. 51(1): 214–223.

Ead S, Rajaratnam N, Katopodis C. 2002. Generalized study of hydraulics of culvert fishways. J Hydraul Eng. 128(11):1018–1022.

Enders EC, Castro-Santos T, Lacey RJ. 2017. The effects of horizontally and vertically oriented baffles on flow structure and ascent performance of upstream-migrating fish. J Ecohydraulics. 2(1):38–52.

Feurich R, Boubée J, Olsen N. 2011. Spoiler baffles in circular culverts. J Environ Eng. 137(9):854–857.

Feurich R, Boubée J, Olsen N. 2012. Improvement of fish passage in culverts using CFD. Ecol Eng. 47:1–8.

Franklin PA, Bartels B. 2012. Restoring connectivity for migratory native fish in a New Zealand stream: effectiveness of retrofitting a pipe culvert. Aquatic Conserv: Mar Freshw Ecosyst. 22(4):489–497.

Franklin PA, Gee E. 2019. Living in an amphidromous world: Perspectives on the management of fish passage from an island nation. Aquat Conserv: Mar Freshw Ecosyst. 29(9):1424–1437.

Franklin PA, Gee E, Baker CF, Bowie S. 2018. New Zealand fish passage guidelines—For structures up to 4 meters. Hamilton (NZ): NIWA.

Fuentes-Pérez JF, Tuhtan JA, Carbonell-Baeza R, Musall M, Toming G, Muhammad N, Kruusmaa M. 2015. Current velocity estimation using a lateral line probe. *Ecological Engineering* 85:296–300.

Fuentes-Pérez JF, Eckert M, Tuhtan JA, Ferreira MT, Kruusmaa M, Branco P. 2018. Spatial preferences of Iberian barbel in a vertical slot fishway under variable hydrodynamic scenarios. Ecol Eng. 125:131–142.

Gibson RJ, Haedrich RL, Wernerheim CM. 2005. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. Fisheries. 30(1):10–17.

Goettel MT, Atkinson JF, Bennett SJ. 2015. Behavior of western blacknose dace in a turbulence modified flow field. Ecol Eng. 74:230–240.

Goodrich HR, Watson JR, Cramp RL, Gordos MA, Franklin CE. 2018. Making culverts great again. Efficacy of a common culvert remediation strategy across sympatric fish species. Ecol Eng. 116:143–153.

Habit E, Piedra P, Ruzzante DE, Walde SJ, Belk MC, Cussac VE, Gonzalez J, Colin N. 2010. Changes in the distribution of native fishes in response to introduced species and other anthropogenic effects. Global Ecol Biogeogr. 19(5):697–710.

Harpaz R, Tkačik G, Schneidman E. 2017. Discrete modes of social information processing predict individual behavior of fish in a group. Proc Natl Acad Sci Usa. 114(38):10149–10154.

Hockley FA, Wilson C, Brew A, Cable J. 2014. Fish responses to flow velocity and turbulence in relation to size, sex and parasite load. J R Soc Interface. 11(91): 20130814.

Januchowski-Hartley SR, McIntyre PB, Diebel M, Doran PJ, Infante DM, Joseph C, Allan JD. 2013. Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. Front Ecol Environ. 11(4):211–217.

Johnson GE, Pearson WH, Southard SL, Mueller RP. 2012. Upstream movement of juvenile coho salmon in relation to environmental conditions in a culvert test bed. Trans Am Fish Soc. 141(6):1520–1531.

Johnson K, Wait LE, Monk SK, Rader R, Hotchkiss RH, Belk MC. 2019. Effects of substrate on movement patterns and behaviour of stream fish through culverts: An experimental approach. Sustainability. 11(2):470.

Kapitzke R. 2007. Multipurpose design for fish passage at road crossings on a north Queensland stream. Aust J Multidiscip Eng. 5(1):13–19.

Katopodis C, Kells J, Acharya M. 2001. Nature-like and conventional fishways: alternative concepts? Can Water

Resour J/Revue Canadienne Des Ressources Hydriques. 26(2):211–232.
Katopodis C, Williams JG. 2012. The development of fish passage research in a historical context. Ecol Eng. 48: 8–18.
Kemp PS. 2012. Bridging the gap between fish behaviour, performance and hydrodynamics: an ecohydraulics approach to fish passage research. River Res Applic. 28(4):403–406.
Kemp PS. 2016. Meta-analyses, metrics and motivation: Mixed messages in the fish passage debate. River Res Applic. 32(10):2116–2124.
Khodier MA, Tullis BP. 2014. Fish passage behavior for severe hydraulic conditions in baffled culverts. J Hydraul Eng. 140(3):322–327.
Knapp M, Montgomery J, Whittaker C, Franklin P, Baker CF, Friedrich H. 2019. Fish passage hydrodynamics: insights into overcoming migration challenges for small-bodied fish. J Ecohydraulics. 4(1):43–406.
Lacey RJ, Neary VS, Liao JC, Enders EC, Tritico HM. 2012. The IPOS framework: linking fish swimming performance in altered flows from laboratory experiments to rivers. River Res Applic. 28(4):429–443.
Lacey RJ, Rennie CD. 2012. Laboratory investigation of turbulent flow structure around a bed-mounted cube at multiple flow stages. J Hydraul Eng. 138(1):71–84.
Larousse A, Martinuzzi R, Tropea C. 1991. Flow around surface-mounted, three-dimensional obstacles. Selected Papers of the 8th Symposium on Turbulent Shear Flows. Springer; p. 127–139.
Leng X, Chanson H. 2019. Hybrid modelling of low velocity zones in box culverts to assist upstream fish passage. Environ Fluid Mech. doi:10.1007/s10652-019-09700-1
Liao JC. 2006. The role of the lateral line and vision on body kinematics and hydrodynamic preference of rainbow trout in turbulent flow. J Exp Biol. 209(20): 4077–4090.
Liao JC. 2007. A review of fish swimming mechanics and behaviour in altered flows. Phil Trans R Soc B. 362(1487):1973–1993.
Liao JC, Beal DN, Lauder GV, Triantafyllou MS. 2003a. Fish exploiting vortices decrease muscle activity. Science. 302(5650):1566–1569.
Liao JC, Beal DN, Lauder GV, Triantafyllou MS. 2003b. The Kármán gait: novel body kinematics of rainbow trout swimming in a vortex street. J Exp Biol. 206(6): 1059–1073.
Link O, Sanhueza C, Arriagada P, Brevis W, Laborde A, González A, Wilkes M, Habit E. 2017. The fish Strouhal number as a criterion for hydraulic fishway design. Ecol Eng. 103:118–126.
Lupandin A. 2005. Effect of flow turbulence on swimming speed of fish. Biol Bull Russ Acad Sci. 32(5):461–466.
MacDonald J, Davies P. 2007. Improving the upstream passage of two galaxiid fish species through a pipe culvert. Fisheries Manage. 14(3):221–230.
Maia A, Sheltzer AP, Tytell ED. 2015. Streamwise vortices destabilize swimming bluegill sunfish (*Lepomis macrochirus*). J Exp Biol. 218(Pt 5):786–792.
Mallen-Cooper M, Brand D. 2007. Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? Fish Manage Ecol. 14(5):319–332.
Martinuzzi R, Tropea C. 1993. The flow around surface-mounted, prismatic obstacles placed in a fully developed channel flow. Transact Am Soc Mech Eng J Fluids Eng. 115:85–85.
Mitchell C. 1989. Swimming performances of some native freshwater fishes. N Z J Mar Freshw Res. 23(2): 181–187.
Muhawenimana V, Wilson C, Ouro P, Cable J. 2019. Spanwise cylinder wake hydrodynamics and fish behaviour. Water Resour Res. 55(11):8569–8582.
Muraoka K, Nakanishi S, Kayaba Y. 2017. Boulder arrangement on a rocky ramp fishway based on the swimming behaviour of fish. Limnologica. 62:188–193.
New Zealand Transport Agency. 2013. Fish passage guidance for state highways. New Zealand: New Zealand Transport Agency.
Newbold L, Karageorgopoulos P, Kemp P. 2014. Corner and sloped culvert baffles improve the upstream passage of adult European eels (*Anguilla anguilla*). Ecol Eng. 73:752–759.
Nikora VI, Aberle J, Biggs B, Jowett I, Sykes J. 2003. Effects of fish size, time-to-fatigue and turbulence on swimming performance: a case study of *Galaxias maculatus*. J Fish Biol. 63(6):1365–1382.
Noonan MJ, Grant JW, Jackson CD. 2012. A quantitative assessment of fish passage efficiency. Fish Fish. 13(4): 450–464.
Olsen A, Tullis B. 2013. Laboratory study of fish passage and discharge capacity in slip-lined, baffled culverts. J Hydraul Eng. 139(4):424–432.
Ovidio M, Sonny D, Dierckx A, Watthez Q, Bourguignon S, de Le Court B, Detrait O, Benitez JP. 2017. The use of behavioural metrics to evaluate fishway efficiency. River Res Applic. 33(9):1484–1493.
Przybilla A, Kunze S, Rudert A, Bleckmann H, Brücker C. 2010. Entraining in trout: a behavioural and hydrodynamic analysis. J Exp Biol. 213(17):2976–2986.
Qian Z-M, Chen YQ. 2017. Feature point based 3D tracking of multiple fish from multi-view images. PloS One. 12(6):e0180254.
Quaresma AL, Romão F, Branco P, Ferreira MT, Pinheiro AN. 2018. Multi slot versus single slot pool-type fishways: a modelling approach to compare hydrodynamics. Ecol Eng. 122:197–206.
Rajaratnam N, Katopodis C. 1990. Hydraulics of culvert fishways III: weir baffle culvert fishways. Can J Civ Eng. 17(4):558–568.
Rajaratnam N, Katopodis C, Fairbairn M. 1990. Hydraulics of culvert fishways V: Alberta fish weirs and baffles. Can J Civ Eng. 17(6):1015–1021.
Rajaratnam N, Katopodis C, Lodewyk S. 1988. Hydraulics of offset baffle culvert fishways. Can J Civ Eng. 15(6): 1043–1051.
Rajaratnam N, Katopodis C, Lodewyk S. 1991. Hydraulics of culvert fishways IV: spoiler baffle culvert fishways. Can J Civ Eng. 18(1):76–82.
Rajaratnam N, Katopodis C, McQuitty N. 1989. Hydraulics of culvert fishways II: slotted-weir culvert fishways. Can J Civ Eng. 16(3):375–383.
Rodgers EM, Heaslip BM, Cramp RL, Riches M, Gordos MA, Franklin CE. 2017. Substrate roughening improves swimming performance in two small-bodied riverine fishes: implications for culvert remediation and design. Conserv Physiol. 5(1):cox034.
Sadeque M, Rajaratnam N, Loewen M. 2008. Flow around cylinders in open channels. J Eng Mech. 134(1):60–71.
Sadeque M, Rajaratnam N, Loewen MR. 2009. Shallow turbulent wakes behind bed-mounted cylinders in open channels. J Hydraulic Resh. 47(6):727–743.

Sailema C, Freire R, Chanson H, Zhang G. 2019. Modelling small ventilated corner baffles for box culvert barrel. Environ Fluid Mech. doi:10.1007/s10652-019-09680-2.

Santos JM, Branco P, Katopodis C, Ferreira T, Pinheiro A. 2014. Retrofitting pool-and-weir fishways to improve passage performance of benthic fishes: effect of boulder density and fishway discharge. Ecol Eng. 73:335–344.

Shamloo H, Rajaratnam N, Katopodis C. 2001. Hydraulics of simple habitat structures. J Hydraulic Res. 39(4):351–366.

Shen H, Zydlewski GB, Viehman HA, Staines G. 2016. Estimating the probability of fish encountering a marine hydrokinetic device. Renewable Energy. 97:746–756.

Shi X, Xu J, Huang Z, Katopodis C, Ban X, Kynard B, Tan J, Zhu H, Lin C. 2019. A computer-based vision method to automatically determine the 2-dimensional flow-field preference of fish. J Hydraulic Res. 57(4):598–602.

Silva AT, Lucas MC, Castro-Santos T, Katopodis C, Baumgartner LJ, Thiem JD, Aarestrup K, Pompeu PS, O'Brien GC, Braun DC, et al. 2018. The future of fish passage science, engineering, and practice. Fish Fish. 19(2):340–362.

Silva AT, Santos JM, Ferreira MT, Pinheiro AN, Katopodis C. 2011. Effects of water velocity and turbulence on the behaviour of Iberian barbel (*Luciobarbus bocagei*, Steindachner 1864) in an experimental pool-type fishway. River Res Applic. 27(3):360–373.

Smith DL, Brannon EL, Odeh M. 2005. Response of juvenile rainbow trout to turbulence produced by prismatoidal shapes. Trans Am Fish Soc. 134(3):741–753.

Stevenson C, Baker CF. 2009. Fish passage in the Auckland region–a synthesis of current research. Auckland Regional Council Technical Report 2009/84. Prepared by NIWA for Auckland Regional Council. Hamilton. Auckland: National Institute of Water & Atmospheric Research.

Stevenson C, Kopeinig T, Feurich R, Boubée J. 2008. Culvert Barrel Design to Facilitate the Upstream Passage of Small Fish. Auckland Regional Council Technical Publication No. 366, Auckland, New Zealand, 44 pp.

Tonkin JD, Wright LA, David BO. 2012. Mussel spat ropes assist redfin bully Gobiomorphus huttoni passage through experimental culverts with velocity barriers. Water. 4(3):683–689.

Tritico HM, Cotel AJ. 2010. The effects of turbulent eddies on the stability and critical swimming speed of creek chub (*Semotilus atromaculatus*). J Exp Biol. 213(13):2284–2293.

Vowles AS, Karageorgopoulos P, Kemp PS. 2019. Upstream movement of river lamprey through a culvert retrofitted with spoiler baffles under experimental conditions. J Ecohydraulics. 4:1–9.

Vowles AS, Karlsson SP, Uzunova EP, Kemp PS. 2014. The importance of behaviour in predicting the impact of a novel small-scale hydropower device on the survival of downstream moving fish. Ecol Eng. 69:151–159.

Wang H, Chanson H. 2018. Modelling upstream fish passage in standard box culverts: Interplay between turbulence, fish kinematics, and energetics. River Res Applic. 34(3):244–252.

Warren Jr ML, Pardew MG. 1998. Road crossings as barriers to small-stream fish movement. Trans Am Fish Soc. 127(4):637–644.

Watson JR, Goodrich HR, Cramp RL, Gordos MA, Franklin CE. 2018. Utilising the boundary layer to help restore the connectivity of fish habitats and populations. Ecol Eng. 122:286–294.

Webb P. 1998. Entrainment by river chub Nocomis micropogon and smallmuth bass *Micropterus dolomieu* on cylinders. J Exp Biol. 201(16):2403–2412.

Webb P, Cotel A. 2010. Turbulence: does vorticity affect the structure and shape of body and fin propulsors? Integr Comp Biol. 50(6):1155–1166.