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 behavior 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 behavior (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, transboundary 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
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...
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.

Figure 1. Processes that govern the effectiveness of individual fish passage at various scales.
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 1. Overview of studies performed to understand fish behaviour in turbulent flow condition using different turbulent generators.

<table>
<thead>
<tr>
<th>Species/ taxa tested</th>
<th>Body length (cm)</th>
<th>Turbulent generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Webb (1998)</td>
<td></td>
<td>Vertically and horizontally oriented cylinders of 0.64, 1.3, 2.5 cm diameter.</td>
</tr>
<tr>
<td>Liao et al. (2003b)</td>
<td></td>
<td>D shaped cylinder of 2.5 and 5 cm diameter.</td>
</tr>
<tr>
<td>Lupandin (2005)</td>
<td></td>
<td>Turbulent property of the flow controlled by special device.</td>
</tr>
<tr>
<td>Smith et al. (2005)</td>
<td></td>
<td>Prismatical shape formed by bricks.</td>
</tr>
<tr>
<td>Przybilla et al. (2010)</td>
<td></td>
<td>Semi-infinite flat plate of length (L × H: 35 × 40 cm).</td>
</tr>
<tr>
<td>Tritico and Cotel (2010)</td>
<td></td>
<td>Cylinders of 0.4, 1.6 and 8.9 cm diameter</td>
</tr>
<tr>
<td>Goettel et al. (2015)</td>
<td></td>
<td>Turbulence created by bricks of dimension (L × B × H: 20 × 10 × 5.5 cm)</td>
</tr>
<tr>
<td>Maia et al. (2015)</td>
<td></td>
<td>Rotating turbine of 6 cm diameter</td>
</tr>
<tr>
<td>Link et al. (2017)</td>
<td></td>
<td>Vertical cylinders:</td>
</tr>
<tr>
<td>Muhawenimana et al. (2019)</td>
<td></td>
<td>Horizontal cylinder of 5 cm diameter</td>
</tr>
</tbody>
</table>

L: length, B: width, H: height
Table 2. Overview of assessment of fish passage through small-scale structures with different roughness elements in laboratory setups.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Species/ taxa tested</th>
<th>Hydraulic structures</th>
<th>Roughness elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MacDonald and Davies (2007)</td>
<td><em>Galaxias maculatus</em></td>
<td>Culvert (L × Ø)</td>
<td>Spoiler baffles (L × B × H):</td>
</tr>
<tr>
<td></td>
<td><em>Galaxias truttaeus</em></td>
<td>5.5 × 1.5 m</td>
<td>100 × 70 × 56 mm</td>
</tr>
<tr>
<td>Franklin and Cabonce et al. (2018)</td>
<td><em>Galaxias maculatus</em></td>
<td>Culvert (L × Ø)</td>
<td>100 × 70 × 28 mm</td>
</tr>
<tr>
<td>Enders et al. (2017)</td>
<td><em>Alosa pseudoharengus</em></td>
<td>Culvert (L × B × H):</td>
<td>Quarter of a cylinder with a radius 0.09 m</td>
</tr>
<tr>
<td></td>
<td><em>Salvelinus fontinalis</em></td>
<td>Culvert (L × Ø):</td>
<td>placed vertically at the wall or horizontally at bed.</td>
</tr>
<tr>
<td>Amstaaetor et al. (2017)</td>
<td><em>Galaxias species</em></td>
<td>Culvert (L × Ø):</td>
<td>Metal sheet:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 × 1.2 m</td>
<td>Covering 25 % of culvert (bottom centre to half way up) on one side.</td>
</tr>
<tr>
<td>Cabonce et al. (2018)</td>
<td><em>Bidyanus bidyanus</em></td>
<td>Horizontal flumes (L × B):</td>
<td>Triangular corner baffle (H)</td>
</tr>
<tr>
<td>Vowles et al. (2019)</td>
<td><em>Lampetra fluviatilis</em></td>
<td>Culvert (L × Ø):</td>
<td>0.133 m with and without hole</td>
</tr>
<tr>
<td>Tonkin et al. (2012)</td>
<td><em>Gobiomorphus huttoni</em></td>
<td>Laboratory culvert (L: 3m and 6m, Ø: 0.35 m)</td>
<td>Gravel, Cordrain®; Sand, Miradrain® and Brush</td>
</tr>
</tbody>
</table>

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 Coté 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
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 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.

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.
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...
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; Sadeqee 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.

![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).](image)
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 anguilla) 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; Triticco 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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