



Fish passage hydrodynamics: insights into overcoming migration challenges for small-bodied fish

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ABSTRACT

The modification and utilization of rivers in regions where small-bodied diadromous fish are prevalent has largely occurred without fully understanding the migration behaviour of these species. As a result, existing in-stream structures often prevent or restrict migration. Current fish passage design guidance generally focuses on providing average hydrodynamic conditions within the range of known critical swimming velocities for target fish species. Considerable portions of discharge capacity must be sacrificed to achieve average cross-sectional water velocities that will allow passage of weak swimmers. Furthermore, because the hydrodynamic requirements for small-bodied species are poorly understood, successful passage is still not guaranteed even when average hydrodynamic design criteria are met. Ethohydraulic research is focused on how water flow influences fish behaviour and vice versa, by studying the interaction of fish with small-scale in-flow characteristics. We discuss how an ethohydraulic approach may improve fish passage design for small-bodied fish, such as inanga/common galaxias (*Galaxias maculatus*), a widespread diadromous Southern Hemisphere species. The ethohydraulic approach is discussed in detail for culverts, a commonly found structure known to impede fish passage for many small-bodied species.

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Introduction

Understanding fish migration between different habitats is important, not only to facilitate conservation efforts focused on fish populations but also for recognizing the wider ecosystem role that those fish have. Structures in and along rivers often impede the migration of fish species up and down rivers. Significant efforts have been made to develop and refine fish passage facilities, such as culverts to provide both discharge capacity and fish passage and to develop dedicated fish passes, particularly for Northern Hemisphere species with high prevalence or economic importance (Noonan et al. 2012). However, research findings for these species and remediation solutions may not extrapolate to other species (Birnie-Gauvin et al. 2018; Goodrich et al. 2018; Silva et al. 2018). This is particularly true for small-bodied fish, where we use the term to include adult fish and any juveniles with a body length of below 15 cm. For amphidromous or catadromous species, which often undertake upstream migrations as small juveniles (often <60 mm), a significant lack of research has frequently been noted (e.g. Walter

et al. 2012; Miles et al. 2013; Franklin and Gee 2019). This lack of knowledge to inform the design of in-stream structures or fish passes that enable unimpeded upstream migration of small-bodied fish is compounded by the pressure towards land development from rapid economic expansion (Wilkes et al. 2017; Habit et al. 2018). In the course of this expansion, rivers are harnessed and modified with a significant effect on the ecosystem.

While large dams are often cited as critical disruptions to river connectivity (e.g. Winemiller et al. 2016), river crossings are far more prevalent and regularly impede fish migrations (Birnie-Gauvin et al. 2018). River crossings are commonly designed for maximum cost efficiency meaning that bridges or a stream simulation design (i.e. that mimics natural stream conditions and processes within the culvert), which would be the preferable solution from a fish passage perspective, are not used (Deutsche Vereinigung für Wasserwirtschaft 2014; Franklin et al. 2018). Instead they are often designed as simple structures, consisting of an embankment with an embedded smooth culvert. Because of their high cost-efficiency, such simple culvert designs are

predominant, especially in rural areas and for smaller rivers and streams. The high discharge efficiency of culverts is associated with high water velocities, uniform flow conditions and subsequently low prospects of successful passage for weak swimming fish. This is aggravated for small-bodied fish, as the maximum swimming speed of fish species generally correlates to their body length (Righton et al. 2013). Furthermore, shallow water depths and perching of culvert outlets present additional migration challenges for fish, with the passage of small-bodied fish impeded by drops of as little as 50 mm (Baker 2003). In contrast, remediation of culverts to allow the passage of fish risks disrupting the discharge rate and reducing the culverts' hydrodynamic efficiency. This in turn leads to increased risk of flooding during high discharge events, potentially causing damage to infrastructure and private property.

To address this conflict and drive research into designs that satisfy both ends of the spectrum – fish passage efficiency and discharge efficiency – the emerging study field of ethohydraulics can be incorporated into fish passage research. Ethohydraulics – a portmanteau of 'ethology', the study of animal motions, and 'hydraulics' (a term encompassing both hydrodynamic and hydrostatic effects) – focus on how water flow influences fish behaviour and vice versa. This involves studying the interaction of small-scale in-flow characteristics, such as turbulence length scale and vorticity, and fish swimming behaviour and performance. Benefits that this approach to hydrodynamics in fish passage can have for culvert remediation will be discussed in this paper. The focus regarding culvert remediation will be on fish passage for small-bodied diadromous fish, which are especially affected by culverts with high discharge efficiency. To provide a practical point of reference, the situation of fish passage in New Zealand will be discussed in detail but the deliberations are equally applicable to a broader range of ecosystems that are habitat to small-bodied diadromous fish species.

This paper aims to

1. Review the influence of localized hydrodynamic effects on fish passage and how they are considered in fish passage design and evaluation.
2. Provide an overview of the current state of experimental hydrodynamic research for small-bodied fish, in light of ethohydraulics.
3. Examine issues that arise for culvert remediation, in particular for small-bodied diadromous fish, using examples from New Zealand as a case study.

Hydrodynamics in fish passage design

There has been significant effort to research hydrodynamics of fish passage for the more widespread and economically significant species of the Northern Hemisphere, particularly members of the family Salmonidae (e.g. Plaut 2001; Haro et al. 2004; Castro-Santos 2005). However, studies into fish passage commonly focus on the critical fish swimming speed, meaning the swimming speed at which fish start exhibiting exhaustion, or swimming endurance meaning the amount of time that a fish can uphold a specific speed before fatigue. This has informed numerous guidelines for fish passage design with critical fish swimming speeds or swimming endurance used as the basis for recommendations for average water velocity and sometimes turbulent energy dissipation design criteria within fish passes or culverts (e.g. Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. 2002; Washington Department of Fish and Wildlife 2003; Deutsche Vereinigung für Wasserwirtschaft 2014; Franklin et al. 2018). The challenge such a design approach presents is that small-bodied fish, due to their size, have accordingly low critical swimming speeds (Nikora et al. 2003). Following the guidelines would either result in culverts with average flow rates that are not economically feasible when built in accordance with critical swimming speeds of small-bodied fish, or it would result in culverts that are impassable for the weakest swimmers when built with stronger swimmers in mind. The latter is usually the case, and consequently, designs whose success has already been questionable for stronger swimmers are failing to accommodate the weakest swimmers in regions where small-bodied species are present (e.g. Mallen-Cooper and Brand 2007).

A solution requires not only learning why existing designs fail for small-bodied fish, but also the evaluation of new designs that are specifically geared towards smaller fish, by building on this knowledge. To analyze the reasons for failure or success of a specific fish pass or culvert design, it is crucial to understand the hydrodynamic conditions within, and the behaviour of fish when confronted with these conditions. However, field observations of these parameters are seldom available (Noonan et al. 2012; Wilkes et al. 2017). This lack of data is likely caused by the difficulty of setting up elaborate testing equipment in the field for any length of time, as it may be subjected to harsh weather conditions, and theft or vandalism. Furthermore biotelemetry techniques that involve tagging and tracking fish movements are not feasible for small-bodied fish (Jellyman 2009; Baker et al. 2017) and parameters that may influence fish movement, such as water temperature or discharge rate, cannot be controlled.

Table 1. Overview of studies capturing the flow field for the purpose of correlation with fish swimming performance (ethohydraulics) to evaluate fish passage including typical body size of species as adults.

Paper	Species/taxa tested	Adult body length (cm)	Data acquisition
Wang et al. (2016)	<i>Bidyanus bidyanus</i> ,	~30	ADV for velocimetry
	<i>Melanotaenia duboulayi</i>	~8	Video footage with automated extraction of fish kinematics
Goodrich et al. (2018)	<i>Melanotaenia duboulayi</i> ,	~8	Combination of pitot tube and vane wheel for velocimetry
	<i>Hypseleotris compressa</i> ,	~5	Video footage with manual, grid based extraction of fish kinematics
	<i>Tandanus tandanus</i> ,	~45	
	<i>Maccullochella peelii</i>	~60	
Cabonce et al. (2018)	<i>Bidyanus bidyanus</i>	~30	Combination of pitot tube and ADV for velocimetry
			Video footage with automated extraction of fish kinematics
Muraoka et al. (2017)	<i>Salvelinus richardson</i> ,	NA	PIV for velocimetry
		NA	Video footage with automated extraction of fish kinematics
Link et al. (2017)	<i>Cheirodon galusdae</i> ,	~5	PIV for velocimetry
		~25	Video footage with automated extraction of fish kinematics
Hockley et al. (2014)	<i>Poecilia reticulata</i>	~3	ADV for velocimetry
Goettel et al. (2014)	<i>Rhinichthys obtusus</i>	~8	ADV for velocimetry
			Video footage with manual, grid based extraction of fish kinematics
Tritico and Cotel (2010)	<i>Semotilus atromaculatus</i>	~20	PIV for velocimetry
			Video footage with manual extraction of fish kinematics
Watson et al. (2018)	<i>Macquaria ambigua</i>	~45	ADV for velocimetry
	<i>Maccullochella peelii</i>	~55	Video footage with manual extraction of fish kinematics
	<i>Tandanus tandanus</i>	~45	
	<i>Hypseleotris compressa</i>	~5	
	<i>Ambassis agassizii</i>	~5	
	<i>Pseudomugil signifer</i>	~3	
Duguay et al. (2018)	<i>Oncorhynchus mykiss</i>	~60	PIV for velocimetry
			Video footage with automated extraction of fish kinematics

The investigation of fish passage success relative to culvert or fish pass hydrodynamics with specially constructed flumes under laboratory conditions, has garnered increased popularity in recent years (Tonkin et al. 2012; Olsen and Tullis 2013; Baker 2014; Goettel et al. 2014; Duguay and Lacey 2015; Khodier and Tullis 2017; Watson et al. 2018). Despite this, design guidelines for fish passage are most often still dominated by averaged values for water velocity, water depths or turbulence intensity, disregarding the spatial and temporal diversity of flow fields within a structure. This motivated the development of the new research area of ethohydraulics. A cornerstone of ethohydraulics is the departure from the high-level approach of assessing the viability of designs for fish facilities through average flow characteristics. Ethohydraulics has also gained increased traction thanks to the availability of relatively inexpensive devices for high-quality video capture, which allows the detailed observation of fish movement and the flow fields they traverse within a laboratory flume, with the appropriate spatial and temporal resolution. Table 1 gives an overview of a non-exhaustive selection of recent studies applying an ethohydraulic approach and the technology used for obtaining

the required data on flow features that can affect fish swimming ability.

Localized low-velocity zones

Locally confined low-velocity zones are thought to play a significant part in the successful upstream passage of fish (Wang et al. 2016; Zhang and Chanson 2018). The discharge capacity of a given cross-section is less affected by the inclusion of locally confined low-velocity zones, compared to an overall reduction of water velocity for a complete cross section (Zhang and Chanson 2018). Due to their size, small-bodied fish can more readily make use of these smaller flow features than larger fish. These low-velocity zones should be evenly distributed, but do not necessarily have to be continuous, to provide fish with rest areas where they can practice so called “flow refuging” along their path upstream (Gerstner 1998). However, evidence for the effect of low-velocity zones on small-bodied fish is scarce and sometimes only anecdotal. As an example, juvenile diadromous fish of the family Galaxiidae, called whitebait in New Zealand, have been observed to be able to swim up an almost vertical, approximately 0.8 m high incline on St Ronans

weir in the Whaiwhetu river, near Wellington (2018 conversation with G Webby and video capture provided by Friends of Waiwhetu Stream; not referenced). For whitebait, which due to their body size (40–60 mm) are weak swimmers, this is a considerable feat, as even fall heights as small as 0.1 m can present an insurmountable barrier to them (Baker 2003). The whitebait were likely able to pass the weir, because of the presence of a thick layer of filamentous algae on the back of the weir, providing a permeable layer of relatively low water velocities for them to ascend the weir. Watson et al. (2018) evaluated several novel designs for the creation of such low-velocity zones near beam-like structures that were inserted just above the corners along the length of box culverts. The results showed that the observed fish species (six small-bodied or juvenile species native to Australia) all benefitted from low-velocity zones created near the beams, as they could be used as stream refuges or ascension corridors. Meanwhile the effect on discharge capacity was comparatively small.

Using dimensional analysis, one of the more recent studies on ethohydraulics (Wang and Chanson 2018) found that energy expenditure of fish can be estimated if fish kinematic and hydrodynamic data are captured with sufficient temporal and spatial resolution. The study was focused on the creation of low-velocity regions, using simple geometries, while the effects of turbulence were not examined in detail. A similar study was conducted with a focus on the effects of bed roughening on discharge capacity (Goodrich et al. 2018). Bed roughening was found to be a viable approach for improving fish passage in culverts while having a minimal effect on discharge capacity and posing less risk of clogging the culvert with debris than baffles would. However, the authors of the study also found that the turbulence that is created through roughening can have a negative effect on some species, by reducing their swimming endurance due to the adverse effects of turbulence on swimming stability, as described further below. Consequently, a generalized roughening approach in culverts that are utilized by several co-existing species should be regarded with caution and instead a design approach that considers inter- and intra-species differences should be followed.

Turbulence influence

Another factor affecting fish swimming performance is the scale and intensity of turbulence in the flow (Nikora et al. 2003). A study by Link et al. (2017) found that two native Chilean fish species exhibited distinctly different swim styles when confronted

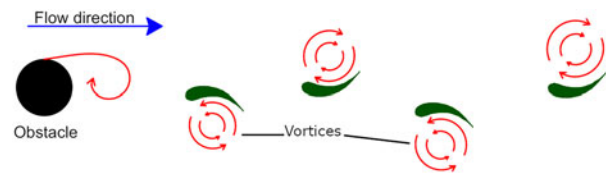


Figure 1. Schematic of how fish can use the alternating rotation and regular structure of von Kármán vortex shedding downstream of an obstacle to their advantage by adjusting their gait to the vortex size and frequency.

with a von Kármán vortex street. While one species managed to partially adapt its swimming gait to the ensuing regular vortex street, thus maintaining stability, the second species was repeatedly destabilized by the turbulence. Adaptation to regular von Kármán turbulence in order to conserve or regenerate energy is known as the Kármán gait (Figure 1) and has been extensively studied in rainbow trout (*Oncorhynchus mykiss*) (Liao et al. 2003; Liao 2007; Liao and Cotel 2013). Fish also use other approaches for saving or regenerating energy, such as bow waking upstream of an obstacle or entraining on either side of one (Trinci et al. 2017). These methods all have in common that fish can anticipate the flow and thus require either a static or regularly periodic flow field. On the other hand, turbulence that is unpredictable for fish can more easily destabilize them. The negative influence of turbulence on fish has for example been discussed by Lupandin (2005), who observed the effects of flow turbulence on the swimming capabilities of perch (*Perca fluviatilis*). The study indicates that body length of the fish and critical turbulence length scale are correlated. Smaller eddies acting on the body of the fish can for the most part balance each other out when the fish travels through them. Larger eddies, at or above the critical turbulence length scale, may exert a torque on the fish (Figure 2) for which there is no counteracting eddy and which consequently creates an imbalance. The fact that the larger eddies also carry the majority of turbulent kinetic energy in a turbulent flow (Leonard 1975) factors into the destabilization of fish as well. For any unbalancing forces, the fish will have to compensate, by increasing their hydrodynamic resistance using the paired fins (Standen 2010; Deutsche Vereinigung für Wasserwirtschaft 2014), which will, in turn, decrease maximum swimming speed.

There are conflicting views on what the critical length scale for fish is. Lupandin (2005) assumed it to be in the order of two-thirds of their body length, while Webb and Cotel (2010) argue that destabilization can already occur at eddy diameters that reach one-fourth of the fish body length. So far, detailed research into critical length scales for species, other than *P. fluviatilis*, has not been undertaken, and it

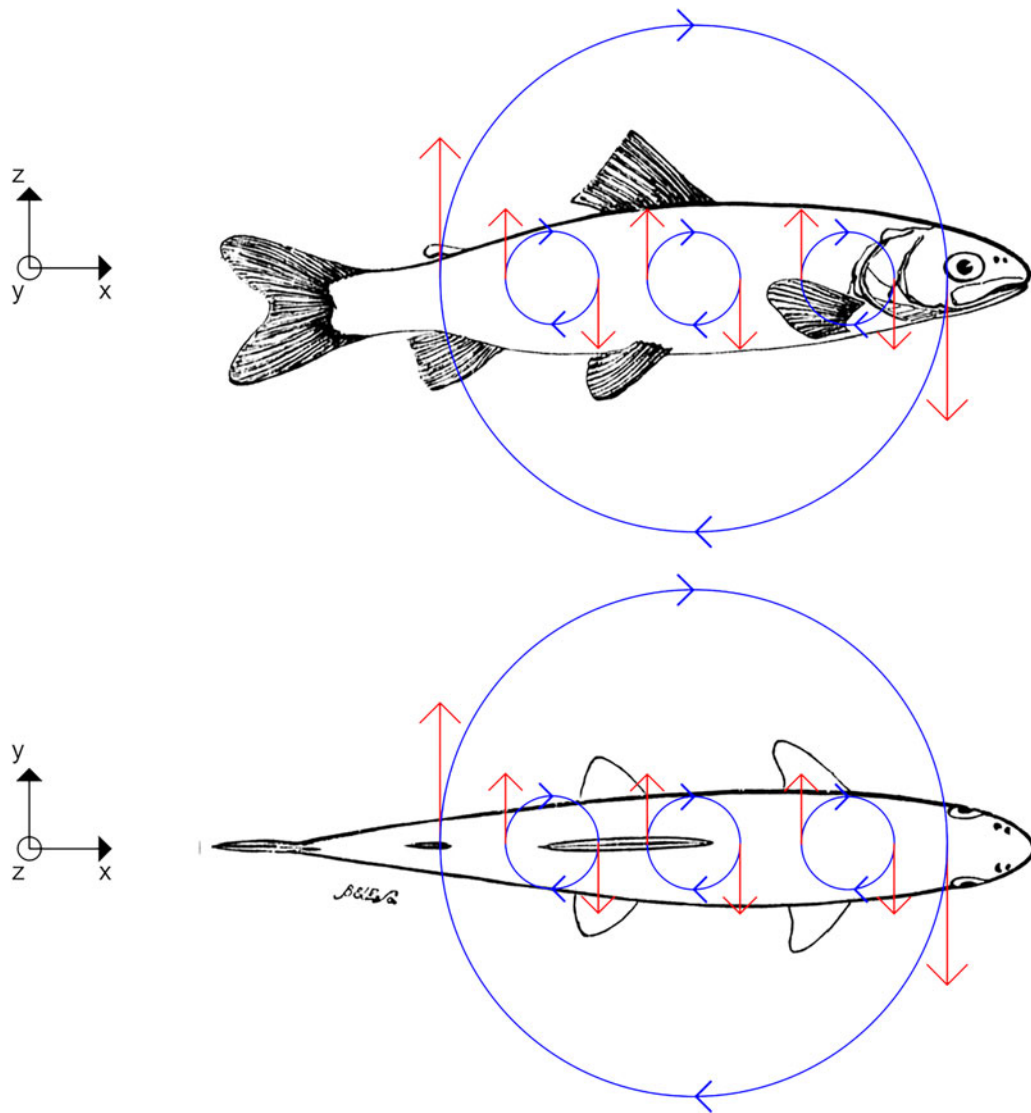


Figure 2. Schematic of turbulent eddies (circles with indication of direction) of different sizes exerting unbalancing forces on the fish (arrows); small eddies will create smaller torque and have little effect on destabilization (Lupandin 2005); (drawing from (Herbert 1851) modified).

has to be assumed that it will largely depend on the examined species. The aforementioned critical length assumes rotation around the z - and y -axes of the fish, as depicted in Figure 2. Eddies rotating around the x -axis may have negative effects at a much smaller scale already, due to the smaller cross-section, and thus smaller moment of inertia, of the fish around its longitudinal axis. Turbulence intensity around the x -axis can be assumed to be comparatively small during fish passage since the longitudinal axis of the fish will generally be aligned with the main flow direction (Pavlov 1989). Turbulence perpendicular to the main flow direction is smaller than parallel to it as there is usually little cross flow in a culvert, contrasting with specific designs such as the Denil fishway, which uses deflectors to redirect parts of the flow perpendicular and opposite to the main flow direction to increase hydrodynamic resistance and diversify the flow field. However, it has also been found by Liao (2007) that

fish can be destabilized by such turbulence. While the results in the study show that high turbulence is more likely to be detrimental to fish swimming speed, low-velocity regions that exhibit high turbulence can still be used by fish as resting areas to recover before their continued ascent (Hockley et al. 2014). Ethohydraulic research supports the long-held view amongst experts that critical fish swimming speed, and other averaged parameters often used in fish pass design, should not serve as the sole guiding principles for fish pass design, as they ignore the beneficial and detrimental effects of small-scale turbulence.

Experimental hydrodynamic research for small-bodied fish

Ideally, fish would be observed in their natural environment, however as described above, these types of observations are difficult to implement,

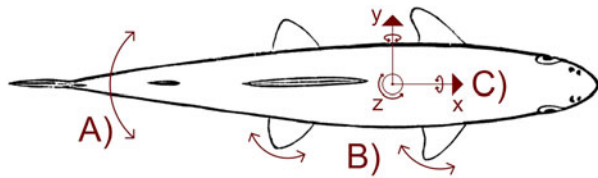


Figure 3. Quantifiable parameters of fish displacement and deformation relating to swimming motion; (A) tail beat frequency and amplitude, (B) fin position, and (C) angular rotation and linear translation.

particularly in small diameter culverts, due to space constraints and limited accessibility. Laboratory studies on the other hand open up a variety of observation methods, ranging from capturing detailed fish movement to the observation of flow patterns in large volumes and high resolution which can be difficult or impossible to implement in the field due to limits in, e.g. the availability of observation perspectives, visibility caused by entrained sediments or access to the structure (such as a culvert) itself. In contrast to field studies, these experiments provide a controlled environment and open new avenues of observation, for example by introducing viewing ports into the design, further benefitting the use of video cameras for data collection. Flow field data can then be captured by techniques such as particle tracking velocimetry (PTV) or particle imaging velocimetry (PIV), which in their basic function work quite similarly, by scattering light off small particles that are moving with the fluid and determining the flow field from the difference between recorded pictures (Jahanmiri 2011). These velocimetry techniques can be applied at characteristic cross-sections, for example behind a baffle or near boundary layers and can generate high-resolution flow fields at any one point in time with comparatively little effort. Thanks to the detailed resolution that is achievable with video-assisted velocimetry, individual vortices of various scales and intensities can be identified (e.g. Fox and Patrick 2008). As the flow field in culverts can be expected to be non-uniform in all three spatial dimensions, especially if more complex geometries are evaluated, it is considered important to capture flow fields in three dimensions (Wang et al. 2016). However, Table 1 demonstrates that techniques like PIV or PTV are not necessarily the main means of data collection in ethohydraulics. The most common technique applied is the acoustic Doppler velocimeter (ADV) which allows point measurements within the flow region of interest. However, the characteristics of ADVs precludes their application in large areas in all three spatial dimensions at a single point in time. Because of this, detailed turbulence measurements, in particular, turbulence length scale or vorticity, are limited (Sokoray-Varga and Józsa 2008).

The studies in Table 1 that do employ PIV are either concerned with isolated turbulence effects rather than a holistic view at hydrodynamics in fish passage (Tritico and Cotel 2010; Link et al. 2017), or do not examine turbulence in detail (Muraoka et al. 2017). The study conducted by Duguay et al. (2018) provides a notable exception, as it evaluates the influence of sediment wedges behind baffles on fish passage, employing large-scale application of PIV to examine turbulence effects and their impact on fish swimming. The results of the study allowed, among others, inference towards the likelihood of an eddy of specific size and rotational frequency to destabilize fish posture. Cotel and Webb (2015) recommend PIV as a convenient and accurate method for capturing the underlying parameters of, e.g. turbulence length scale, vorticity or momentum flux required for characterizing fish-turbulence interaction. Based on the results obtained using PIV in contemporary research discussed in this section, the recommendation for PIV to facilitate flow field capture is shared by the authors of this paper.

Similarly to the requirement of capturing the flow field in three dimensions, as water depth increases and the flow field becomes more heterogeneous, fish will start using more of the available space, and the capture of fish motion should be realized in three dimensions. A method for such three-dimensional tracking has recently been developed and evaluated by Voesenek et al. (2016) and Duguay et al. (2018) demonstrated the application of large scale three-dimensional fish tracking while observing the interaction of juvenile rainbow trout (*O. mykiss*) with baffles in a flume. The capture of high-resolution video footage of the swimming behaviour of fish will not just enable the analysis of extrinsic parameters such as location, dwelling time or velocity/acceleration of fish, but also of other behavioural parameters, such as tail beat amplitude/frequency or paired fin orientation (Standen 2010; Link et al. 2017) as indicated in Figure 3. In addition other exploitation of the flow can be made observable, such as the energy efficient diamond configuration in schools of fish (Fish 2010), which may be particularly relevant for diadromous fish that migrate as juveniles, as schooling tends to be more common among juvenile fish (Pavlov and Kasumyan 2000).

Current state of fish passage design in New Zealand

Similarly to other island nations of the tropics and subtropics, (McDowall 1995; Keith 2003; McDowall 2007; Walter et al. 2012) diadromous species are numerous in New Zealand. Overall 15 of the around

Table 2. Overview of assessed structures vs. presumed structures in the Waikato region (Kelly and Collier 2007).

District	Total number of structures assessed	Number of points where streams and rivers cross roads	Percentage of structures assessed
Franklin District ^a	210	480	43.8
Matamata-Piako District	282	811	34.8
Otorohanga District	133	563	23.6
Thames-Coromandel District	367	779	47.1
Waikato District	403	1245	32.4
Waipa District	219	665	32.9
Total	1614	4543	35.5

^aNow part of Waikato District.

53 known native freshwater fish species in New Zealand are diadromous and of those in turn 13 are either amphidromous, or (marginally) catadromous and therefore undertake upstream migration as juveniles (Dunn et al. 2018). The majority of New Zealand's diadromous species are endemic, with a small number more widely distributed in the Southern Hemisphere. The large number of migration barriers in New Zealand rivers is thought to be a key factor in the observed decline of many freshwater fish species, particularly of the diadromous members of the Family Galaxiidae (Dunn et al., 2018). To be able to counter this decline, it is not only necessary to ensure that new structures provide unhindered passage for fish up- and downstream, but also to remediate or reconstruct existing structures. To that effect New Zealand recently saw the release of national guidelines on fish passage, focusing on structures smaller than 4 m in height (Franklin et al. 2018). These guidelines provide the first national framework of best practice and design principles, both for remediation, new- and reconstruction of in-stream structures, with an emphasis on river crossings as these are among the most numerous migration barriers in New Zealand rivers. Other countries of the Southern Hemisphere face similar issues to New Zealand, having been subjected to rapid economic expansion and land development in recent decades, having a lack of research into native fish species, and a lack of effective and binding guidelines and regulation for enabling fish passage. This has resulted in numerous impassable in-stream structures being built in riverine systems (e.g. O'Brien 2000; New South Wales Department of Primary Industries (AU) 2006; Harris et al. 2017).

Quantifying the overall state of fish passage for these countries is often challenging, as most fish passage surveys only cover isolated structures or individual streams so that little insight can be gained in regard to the situation for larger regions or even nationwide. One survey, covering the Waikato region (roughly 4.5% of New Zealand's total land mass) on the North Island of New Zealand (Kelly and Collier 2007), set out to identify all intersections between roads and streams in six districts within that region. Of the 4543 identified intersections, 1614 were assessed, and 845 or about

52% of these structures, generally culverts, were found to impede fish passage for some or most flow regimes (Table 2). This proportion is roughly in line with as of yet unpublished data from the National Institute of Water and Atmospheric Research (NIWA), which shows that around 42% of assessed culverts all over New Zealand presented a migration barrier to some extent (4640 assessed in total).

The role of whitebait

Whitebait is a term that is used worldwide, but the species included therein tend to differ greatly between regions, especially between Northern and Southern Hemisphere, but the term is generally used to describe the juvenile members of fish species undertaking migrations upriver. Members of the family Galaxiidae, which are not present in the Northern Hemisphere, are often a large constituent of whitebait runs in the Southern Hemisphere. In New Zealand whitebait consists of five species of the family Galaxiidae (Figure 4) of which several species are spread out over multiple regions in the southern hemisphere (Figure 5). Table 3 provides an overview of colloquial names and conservation status for two of the more widespread Galaxias species: *Galaxias maculatus* and *Galaxias brevipinnis*. *G. maculatus* is arguably the most economically significant of the five species in New Zealand, constituting the majority of catches in New Zealand, up to 95% in some regions (Yungnickel 2017). Furthermore *G. maculatus* is one of the most widespread indigenous freshwater fish species in the Southern Hemisphere (Waters et al. 2000) and is also part of whitebait runs in Australia, Chile and Argentina, where they are an important part of recreational or even commercial fishing and aquaculture in some places (Mardones et al. 2008). Due to the size of the migrating individuals, juvenile whitebait that migrate upstream are especially susceptible to migration barriers or changes in water quality that may affect their migration. Despite its long-standing importance to industry and culture, research into whitebait in New Zealand is still ongoing, with many aspects of their lifecycle not entirely understood (Goodman 2018). Their small size and slender shape further complicate field research with juvenile



Figure 4. Galaxiid species that are part of whitebait catchments in New Zealand, with common body lengths for adult specimens as well as for juveniles encountered in whitebait schools; with data from (Dunn et al. 2018); *G. postvectis*, *G. argenteus*, *G. brevipinnis*: ©Stella McQueen, CC BY-SA 4.0; *G. fasciatus*: ©Blueether, CC BY-SA 4.0.

whitebait. *G. maculatus* present a challenge for field research even when they are fully grown, as with a body length of about 10 cm they are the smallest of the five species, precluding or severely limiting the use of electronic passive integrated transponders (PIT) or acoustic tags (Chapman et al. 2006; Jellyman 2009; Jepsen et al. 2015; Baker et al. 2017) in field experiments and most likely requiring manual observation if passage success is to be recorded. Field based mark-recapture studies offer one method for characterizing passage rates of fish at structures as an alternative to biotelemetry approaches. Examples for mark-recapture studies include Amtstaetter et al. (2017) and Franklin and Bartels (2012). While these mark and recapture field trials allow evaluation of the passability of specific designs, they provide little insight into why a design is failing or succeeding in letting fish pass as fine-scale behaviour cannot be characterized. This limits

the applicability of observations to other structures, even if the design proves to be successful. This underlines the importance of ethohydraulic studies, conducted in a laboratory setting, in order to more precisely understand the failure mechanisms for migratory small-bodied species. Juveniles of *G. maculatus* present a fairly widespread example of migratory Galaxiidae and small-bodied fish and make an ideal candidate for ethohydraulic studies. As grown individuals, *G. maculatus* are, at least for New Zealand, considered the benchmark as far as swimming fish species are concerned (Franklin et al. 2018) due to their relatively weak swimming performance and lack of climbing ability.

Fish passage retrofit

Even though comprehensive surveys regarding the total number and type of migration barriers are

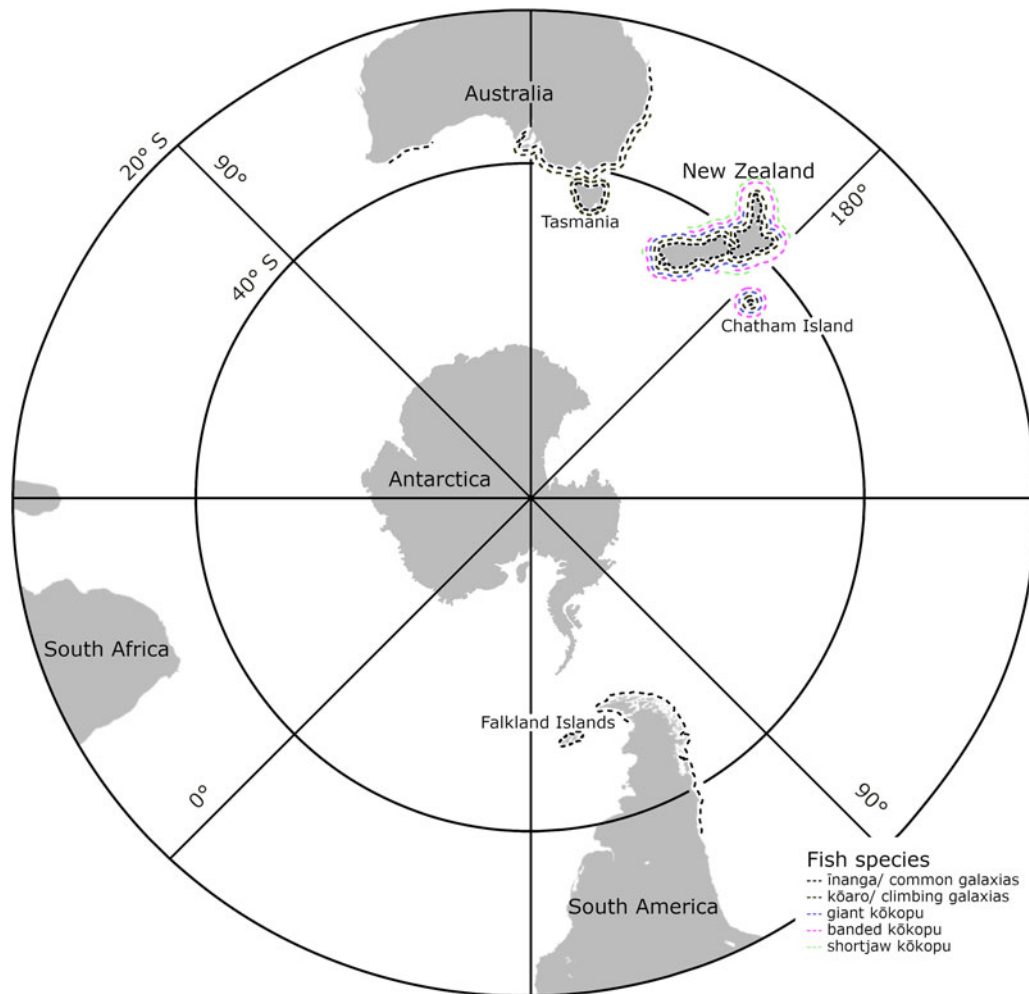


Figure 5. Global distribution of Galaxiidae species that are considered part of whitebait in New Zealand; $\bar{I}$ /common galaxias is present in South America and Australia in addition to New Zealand, while kōaro/climbing galaxias is present in Australia and New Zealand; with data from (McDowall 2002), NIWA, IUCN.

Table 3. Overview of colloquial names and regional conservation status for two of the more widespread Galaxias species that are part of whitebait in New Zealand.

Country/region	Galaxias maculatus			Galaxias brevipinnis		
	Local names		conservation status	Local name		Conservation status
	Adults	Juveniles		Adults	Juveniles	
Argentina	Puyen chico	Cristalinos	Vulnerable (VU) ^a	N/A	N/A	N/A
Australia	Common galaxias, Common jollytail	Whitebait	Not threatened ^b	Climbing galaxias	Whitebait	Not threatened ^b
Chile	Puye	Cristalinos	Vulnerable (VU) northern regions Least Concern (LC) southern regions ^c	N/A	N/A	N/A
Falkland Islands	Falklands minnow	Whitebait	Not threatened ^d	N/A	N/A	N/A
New Zealand	Inanga, Inaka	Whitebait	Declining C(2) ^e	Koaro	Whitebait	Declining C(2) ^e

^aAdministración de Parques Nacionales (AR) (2018).

^bLintermans (2016).

^cMinisterio del Medio Ambiente (1984).

^dBettencourt and Imminga-Berends (2015).

^eDunn et al. (2018).

rarely available, it is evident that existing culverts at river crossings are among the most widespread barriers. Traditional culvert design is characterized by both high water velocities and homogeneous flow fields to maximize discharge efficiency. While removal or re-construction of poorly designed culverts that impede fish passage are the preferred solutions, they will often be impossible or cost-

prohibitive. Another option is remediation of culverts, by including baffles or other devices in their design that create a more heterogeneous flow field that can be utilized by weaker swimmers (e.g. Franklin and Bartels 2012). Culverts being primarily designed for conveyance of specific return interval flow events, means that the discharge capacity should ideally not be impaired by any such designs,

as this could result in capacity overload and subsequent flooding of upstream areas or overtopping of the river crossing in a flood event. Consequently the evaluation of novel designs such as proposed by Watson et al. (2018) should be considered as they generate beneficial flow features that only require a small reduction in discharge capacity, but can provide a viable migration corridor for some species. In particular, localized effects should be examined, such as enhancing low-velocity layers near the culvert boundary, creating beneficial turbulence in a predictable manner and avoiding unpredictable turbulence above the critical turbulence length scale of the target species. Measures such as culvert roughening may also be beneficial to benthic, non-swimming organisms, which typically rely on contact with firm ground for locomotion. Additionally, locally confined interferences have the potential of thwarting the attempts of unwanted predators to cross upstream, as their size may prevent them from taking advantage of smaller scale flow features (Franklin et al. 2018).

Conclusion

It has been demonstrated that particularly in regions of the Southern Hemisphere in-stream structures that pose a migration barrier are ubiquitous, with culverts at river crossings being among the most prevalent. One of the reasons for that is the discrepancy between the high pressure of economic expansion in these countries and a lack of research into native fish species that can inform efficient design regulations for fish passage to achieve connectivity in riverine ecosystems. In combination with a high prevalence of weak swimmers, primarily small-bodied diadromous fish species that undertake upstream migration as small (<60 mm) juvenile fish, the high number of these barriers poses a significant threat to biodiversity. The benefits that ethohydraulic studies can have for remediation of culverts are discussed in this paper, with specific focus towards providing these small-bodied species with a means to migrate upstream. Ethohydraulic studies, correlating fish swimming behaviour with local flow features, are indispensable for understanding the requirements of an observed species. The effect of turbulence or low-velocity zones on the swimming behaviour of most small-bodied fish is still under-researched and should be a focus of future ethohydraulic studies. Observations regarding the critical turbulence length scale are of special interest, as fish with a short body length relative to the expected turbulence length scale can be affected more easily and a low swimming performance means there is little potential for them to counteract destabilizing

forces. This should allow culverts to be remediated for small-bodied fish suitability by using less invasive design measures that originate from these observations.

As a widespread species in South America, New Zealand and Australia, *G. maculatus* are regarded as particularly suitable to act as a benchmark for small-bodied fish, as they are very weak swimmers during upstream migration as juveniles and they cannot climb. Furthermore, the juvenile specimen constitute an important aspect of commercial or recreational fisheries in several countries, e.g. as so-called “whitebait”. It is important to keep in mind that it would be wrong to assume that designs that benefit *G. maculatus* will have the same effect on other small-bodied species, as for example the increased turbulence introduced by measures that help one species, may be too much to cope for another. The success of designs that do benefit them or other small-bodied species can, however, be an indicator for promising approaches, and the combination of designs that work for different species can likewise be considered. Results obtained from ethohydraulic research into small-bodied fish species can complement existing best practice and guidelines. Within New Zealand, the successful implementation of culvert remediation techniques to accommodate small-bodied fish species may in the future very well contribute to their continued survival in the region.

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