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Utilising the boundary layer to help restore the connectivity of fish habitats and populations

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ABSTRACT

Culverts are a major cause of habitat fragmentation in freshwater ecosystems, are a barrier to fish movement, and can be regarded as a significant contributor in the decline of freshwater fish populations globally. To try to address this, various culvert remediation designs have been implemented, including the installation of vertical baffles and the provision of naturalistic (rock) substrates. While remediation strategies generally aim to reduce the velocity of water flowing through the structure, there is often resistance to their use because the resultant reduction in culvert discharge can negatively impact upstream flooding while also resulting in debris clogging and increased culvert maintenance costs. In addition, baffles markedly increase water turbulence that may be detrimental to passage by some fish species or size classes. Here we present some novel remediation designs that exploit the reduced water velocity in boundary layers along the culvert wall to enhance fish passage without significantly compromising discharge capacity. These longitudinal designs produce an expanded reduced velocity zone along the culvert margins that generate minimal turbulence. We show that these novel designs are significantly advantageous to the swimming endurance and traversability for six small-bodied Australian fish species. We also provide data on how and why some culvert baffle designs may impede small-bodied fish passage. This data scales with increasing water velocity, encompassing inter-specific differences in swimming capacity. These results have broad implications for the movement of small-bodied fish species, and the successful recruitment of large-bodied commercially important species, where baffles have been implemented.

1. Introduction

Fish are a ubiquitous component of freshwater ecosystems, the diversity of which means we rely them directly for food, but also on their ecosystem services by maintaining system health, functionality and robustness (Gordon et al., 2018, Obregón et al., 2018, Rodríguez-Lozano et al., 2015). Despite this, freshwater systems are one of the most threatened by human activities (Carpenter et al., 2011). Regulating the flow of freshwater systems to control water access has severely fragmented fish habitats worldwide and threatens the persistence of thousands of freshwater fish species (Butchart et al., 2010, Humphries and Walker, 2013, Katano et al., 2006, Kroon and Phillips, 2015, Liermann et al., 2012). Importantly, movement within and between river, stream and estuarine environments is essential for fish to access critical habitats for reproduction, food and refuge (Humphries and Walker, 2013, Lucas et al., 2009). Anthropogenic modification of waterways can restrict these movements and has led to the fragmentation, decline and local extinction of freshwater fish populations worldwide (Butchart et al., 2010, Humphries and Walker, 2013).

Artificial instream barriers such as dams, weirs and culverts, are major contributors to the loss of freshwater biodiversity. Significant work has focused on designing and implementing fish passes for large-scale barriers (dams and weirs) (Anderson et al., 2015, Loucks, 2012). However, these large structures are substantially outnumbered by low-head barriers, specifically culverts, which are designed to maintain water connectivity under roads, railways and embankments (Lucas et al., 2009). Recent analysis now estimates that these smaller barriers have a greater cumulative impact on fish populations due to their high abundance within freshwater systems (Januchowski-Hartley et al., 2013). This recognition has fuelled the requirement for remediation strategies that work to improve fish passage through culverts (Duguay and Lacey, 2016, Goodrich et al., 2018, Rodgers et al., 2017). Culverts were originally designed to maximise hydraulic capacity with little to no regard for fish passage. Consequently, many culvert designs create a

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Table 1
Attributes of current culvert remediation strategies.

Remediation strategy	How it works to increase fish passage	Pros	Cons
Increasing structure size	• Increased cross-section • Reduces velocities through structure	• Reduces risk of upstream flooding	• Increased capital expenditure • Refurbishment of current structure required
Baffles	• Solid structures generally perpendicular to flow • Provide low velocity rest areas • Create turbulence for kármán gaiting	• Retrofitting opportunities • Cost effective to implement	• Prone to foul with debris • Reduced culvert discharge capacity • Turbulence created is only beneficial for a narrow size class of fish, which is dependent on baffle design and flow characteristics
Bed roughening	• Created by adding natural rocky substrate • Disrupts even flow across an otherwise smooth surface to increase the boundary layer. This creates a low velocity zone near the substrate. Turbulence is also enhanced aiding small-bodied fish to kármán gait	• Can retrofit • Cost effective • Minimal impact on culvert discharge	• Not all fish benefit from turbulence
Addition of ropes	• Increases surface area roughness • Provides substrate for climbing species	• Can retrofit • Cost effective • Minimal impact on culvert discharge	• Limited number of species

hydraulic barrier to fish movement by increasing water velocities and decreasing surface roughness, creating smoother flows through the structure (Rodgers et al., 2014). Recognition of the impact of culverts on fish passage has resulted in the adoption of a range of remediation strategies.

Current culvert remediation strategies include increasing the structure's cross-sectional area to slow water velocities, addition of baffles and ropes, and roughening of the channel bed with naturalistic or artificial substrates (Table 1) (Chanson and Uys, 2016, David et al., 2013, Goodrich et al., 2018, Rodgers et al., 2017, Slawski and Ehlinger, 1998). Strategies employing bed roughening and baffles aim to increase the size and frequency of the low velocity boundary layer (BL) at the culvert margins. A boundary layer is formed from the friction between the water and the solid surface over which it flows. Culvert remediation strategies aim to increase the size of the boundary layer, which creates reduced velocity zones (RVZ's) that fish can exploit (Goodrich et al., 2018, Johnson et al., 2012, Rodgers et al., 2017). These low velocity regions act as energetically favourable movement pathways for fish by reducing the energetic costs associated with swimming in an otherwise high velocity environment. These strategies have proved effective at improving culvert traversability in a number of large bodied commercially important fish species (Johnson et al., 2012), and more recently, for some small-bodied native Australian fishes (Goodrich et al., 2018, Rodgers et al., 2017). In addition to increasing the size of RVZs, baffles, bed roughening and ropes, all create turbulence (Table 1). Turbulence can be defined as the pattern of fluid movement characterised by chaotic changes in flow caused by the interaction of otherwise smooth flow with objects in its path, creating eddies and vortices in its wake. Different fish species respond differently to turbulence, some unfavourably with reduce swimming performance and rates of successful passage (Goodrich et al., 2018, Lupandin 2005, Pavlov et al., 1994, Pavlov et al., 2000). In contrast, some species are able to enhance swimming performance in turbulent flows by utilising eddies (swirling water pockets) to propel themselves forward against water flow via a swimming mode called kármán gaiting (Liao et al., 2003a,b; Taguchi and Liao, 2011). However, for this to strategy to be effective, the eddies must be similar in size to the fish. This restricts the positive effect of turbulence to a certain size class at a particular water velocity, for a specific baffle design. Turbulence does not benefit all fish species, likely due to the interspecific differences in swimming mode, morphology and ecological niche (Goodrich et al., 2018).

While altering velocities and turbulence through the various remediation strategies focuses on the biotic requirements, there are complementing concerns about the impacts of remediation strategies on the civil functionality of culverts, that being their ability to discharge water in a cost effective manner. Both baffles and bed roughening compromise culvert functionality by reducing culvert discharge capacity (Olsen and Tullis, 2013), which can have flow-on impacts on upstream flooding. Additionally, both baffles and bed roughening can also increase the likelihood of debris build up and clogging. This increases the maintenance costs associated with culverts remediated via either strategy and can create a physical barrier to fish passage. Taking into account these civil concerns, the positive effect of larger RVZ, and the mixed effects of turbulence, we designed and tested novel remediation strategies to improve fish passage through culverts.

Previously, we identified that Australian small-bodied and juvenile fish predominantly utilise the RVZ associated with culvert corners (Goodrich et al., 2018). Here the boundary layers of the wall and bed merge to create a larger RVZ that is exploited by the fish to reduce their energy expenditure. Subsequently, we developed novel lateral beam designs that run down the length of the channel to increase the size of the RVZ (Fig. 1). We hypothesised that the longitudinal beams would increase the boundary layer effect to increase the size of RVZ and provide low velocity movement paths for fish. It was hypothesised that fish would actively seek out these regions to enhance their swimming endurance and traversability. Two beams (square and rounded) and a ledge design were created, aimed to enhance the size of the RVZ adjacent to the wall of a 12 m flume while minimising excessive turbulence. We compared these to two triangular baffle treatments, which have been shown to have the best compliance with the civil requirements of available baffle designs (Cabonce et al., 2017, Goodrich et al., 2018).

2. Methods

2.1. Species choice and husbandry

Fishway research has focused predominately on large bodied, commercially important species like salmon and sturgeon (Johnson et al., 2012, May and Kieffer, 2017, Taguchi and Liao, 2011), with small bodied and juvenile fishes representing an important knowledge gap. Small-bodied fish species represent the most threatened size range of fish (Kalinkat et al., 2017, Olden et al., 2007, Ripple et al., 2017), the loss of which would have lasting impacts on ecosystem functionality, health and services (Mouillot et al., 2013, Rodríguez-Lozano et al., 2015). We chose six small bodied or juvenile (< 10 cm total length) native Australian fish species to quantify the effect of our culvert remediation designs: These species are endemic to Australia and