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Making culverts great again. Efficacy of a common culvert remediation strategy across sympatric fish species

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ABSTRACT

Culverts are instream structures that act as hydrological barriers to fish movement by altering water turbulence, increasing water velocities and disrupting connectivity. Hydrological barriers like culverts have led to the fragmentation and decline of freshwater fish populations worldwide. Culvert remediation strategies such as bed roughening have proved effective at increasing the likelihood of fish passage in a variety of fish species. However, little is known about whether culvert roughening is efficacious for Australian small bodied fishes and if so, whether bed roughening is comparably beneficial to all species that may utilise remediated culverts. This study assessed the effect of roughened bed substrates on the swimming performance and behaviour of four small bodied or juvenile Australian fishes (*Hypseleotris compressa* and *Melanotaenia duboulayi*, and juvenile *Tandanus tandanus* and *Maccullochella peelii*) that exist in sympatry over parts of their distribution. Results showed that bed roughening increased water turbulence and the size of low velocity regions within fluid flow and that all fish species displayed the same positive behavioural preferences for these zones. However, the effect of bed roughening on swimming endurance and traversability was found to only benefit *Mel. duboulayi* and *Mac. peelii.* Roughening decreased endurance and traversability in *T. tandanus*, and had no effect on performance in *H. compressa*. These data indicate that sympatric species may respond differently to culvert remediation actions, highlighting the need for a holistic approach to culvert remediation and a comprehensive understanding of all species' requirements within the affected environment.

1. Introduction

Many fish require unimpeded passage within and between river, stream and estuarine environments to complete key aspects of their life cycle, to forage, avoid predation and overcome the effects of competition (Winemiller et al., 2016; Harris et al., 2016). However, anthropogenic modification of waterways through the installation of culverts, weirs and dams disrupts connectivity and has been linked to the decline and/or loss of freshwater fish populations (Pethebridge et al., 1998; Gehrke et al., 2002; Lintermans, 2009; Kroon and Phillips, 2016). Culverts are typically pipe or box shaped structures designed to efficiently pass water below road crossings, but in doing so deleteriously impact fish because of changes to water depth, velocity, and turbulence levels as well as light intensity. (Doehring et al., 2011; Rodgers et al., 2014; Vowles et al., 2014; Kroon and Phillips, 2016). Given the prevalence of culverts and their consequences for fish passage, there is a growing requirement for infrastructure managers to provide proven culvert remediation strategies that will improve fish passage (Harris et al., 2016; Erkinaro et al., 2017).

Culverts often act as hydrodynamic barriers to fish movement by constricting a waterways' cross section, which increases the velocity of water moving through the structure (Feurich et al., 2012; Rodgers et al., 2014; Harris et al., 2016). In addition, contemporary culverts are often made of smooth concrete which causes water flows to become more homogenous as they pass through the structure (Starrs et al., 2011; Feurich et al., 2012; Harris et al., 2016). In natural environments, fish are often exposed to heterogeneous hydrodynamic conditions including, but not limited to, fluctuations in water velocity and direction, and turbulence (Stoesser, 2010). The hydrodynamic heterogeneity in a natural stream system is caused by the interaction of flowing water with rocks, plants, debris and animals. While the term 'turbulence' often has negative connotations, some fish species can reduce their locomotive costs by altering their body kinematics to utilise ('surf') the energy from the eddies in turbulent flows to move against high velocities (Liao et al.,

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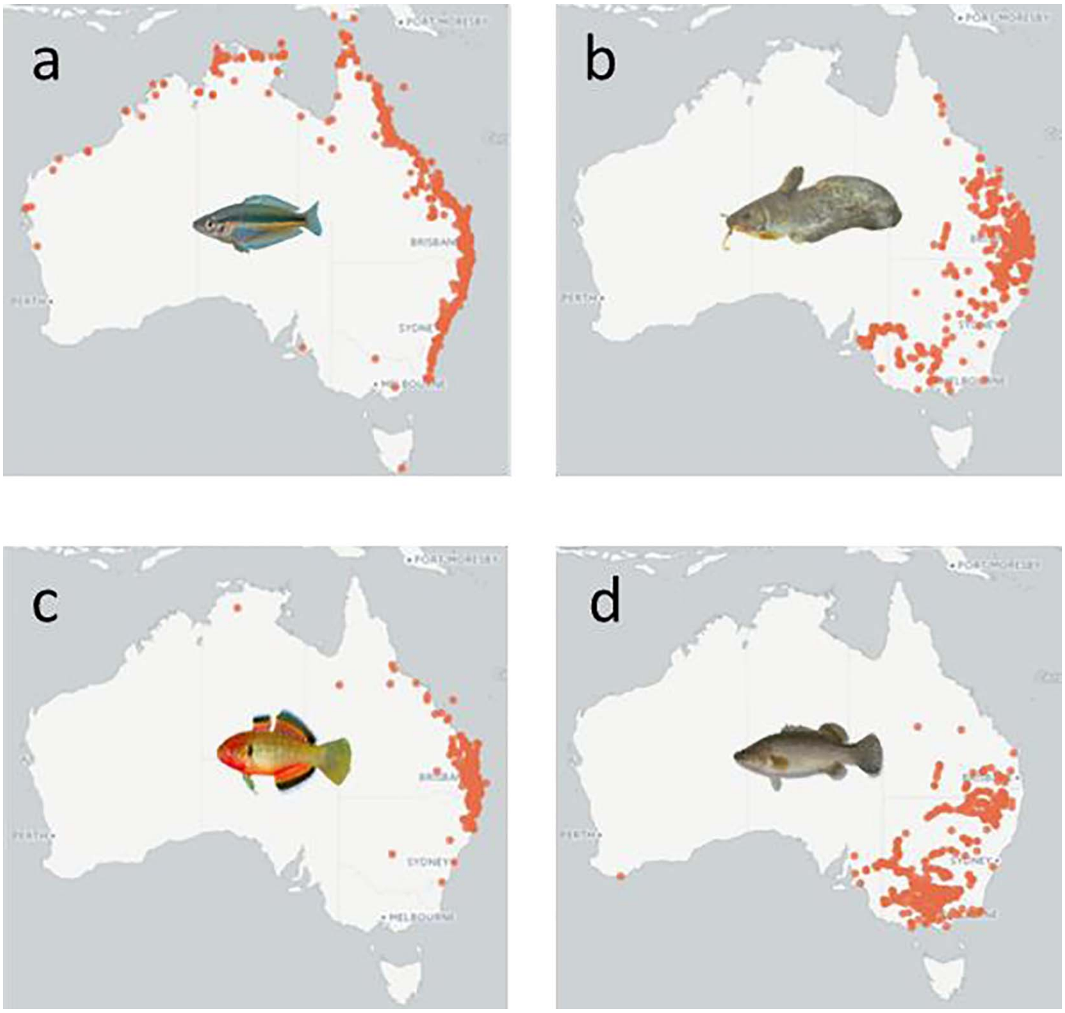

Fig. 1. Distributions of (a) *Melanotaenia duboulayi*, (b) *Tandanus tandanus*, (c) *Hypseleotris compressa* and (d) *Maccullochella peelii* in Australia. This information was adapted from the Atlas of Living Australia (Atlas of Living Australia accessed July 2016: http://www.ala.org.au/).

2003a,b; Taguchi and Liao, 2011).

In addition to their effects on hydrodynamic heterogeneity and water velocity, smooth-sided culverts reduce the thickness of the low velocity boundary layer (reduced velocity gradient) which can have important consequences for fish movement. Low velocity boundary layers (BL) are created from the friction that occurs when a viscous fluid runs along the surface of a solid (Hoerner, 1965). These reduced velocity zones (RVZ) can act as energetically favourable micro-environments that fish can exploit to move against high water velocities (Liao et al., 2003a; Liao, 2007; MacDonald and Davies, 2007; Johnson et al., 2012). Increasing the roughness of the surface along which water is moving can expand boundary layer thickness and in turn, the size of RVZs (Hoerner, 1965; Carlson and Lauder, 2011).

From an engineering perspective, culvert design is largely focused on maintaining or maximising the hydraulic capacity of the structure within its environment, but given the effect this can have on fish movement, novel culvert designs or culvert remediation strategies aimed at improving fish passage are receiving increased attention (Bretón et al., 2013; Duguay and Lacey, 2016; Harris et al., 2016; Erkinaro et al., 2017). Remediation strategies can include increasing the cross sectional area of the culvert to reduce water velocities (current Australian culvert design recommendations suggest water velocities do not exceed $0.3\,m\,s^{-1}$ during base flow conditions (Fairfull and Witheridge, 2003)), creating low velocity 'rest areas' (e.g. baffles) within the culvert, installing fish ladders, or the use of roughened culvert beds. However, remediation strategies can compromise culvert functionality by slowing water flow, altering outflow rates and increasing upstream water depth which may increase the likelihood of flooding (Bates et al., 2003). Using natural substrates (e.g. rocks) to roughen the bed of a culvert is being increasingly employed as a remediation strategy. Providing a more naturalistic culvert bed is relatively cost effective, can maintain culvert functionality and has been shown to increase the likelihood of successful fish passage (Bates et al., 2003; Bretón et al., 2013). It is not clear how broadly efficacious this remediation strategy is for Australian small bodied fish species, given that most existing literature examining the value of naturalistic culvert bed roughening have focused on large bodied, and/or commercially important North American fish species (e.g. Bates and Powers, 1998; Taguchi and Liao, 2011; Johnson et al., 2012; Lacey et al., 2012, Downie and Kieffer, 2017, May and Kieffer, 2017; Erkinaro et al., 2017). Data for North Amercian species like salmon, trout, and sturgeon are unlikely to be reflective of Australian native fishes, most of which are small bodied (< 10 cm total length) and undertake upstream movements during their juvenile stages when their swimming capacity is weakest (Pusey et al., 2004; Humphries and Walker, 2013). Moreover, within and between species differences in swimming ability or performance may determine how well a species can harness the hydrodynamic environment created by culvert bed roughening.

Fish swimming performance (e.g. swimming speed and endurance) can be influenced by a range of abiotic and biotic factors, including body size and shape (Boily and Magnan, 2002), fin form (Plaut, 2000), swimming mode (anguilliform, carangiform or thunniform), swimming

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