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# Paired hydraulically distinct vertical-slot fishways provide complementary fish passage at an estuarine barrier

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ABSTRACT

Facilitating fish passage in fragmented river systems has commonly focused on commercially important migratory species (e.g. salmonids). Increasingly, ecosystem-based approaches to river rehabilitation are being adopted and fishways are progressively being designed for fish assemblages. Estuarine barriers to fish movement have received less attention than riverine barriers in regards to refinement of fish passage. This study evaluated fish passage at a pair of hydraulically distinct vertical-slot fishways (large vertical-slot: max velocity 2.0 m s$^{-1}$, max turbulence 95 W m$^{-3}$, discharge ∼0.36 m$^3$ s$^{-1}$; small vertical-slot: max velocity 1.0 m s$^{-1}$, max turbulence 26 W m$^{-3}$, discharge 0.03 m$^3$ s$^{-1}$) on a low-level (∼1.0 m) estuarine barrier at the terminus of the River Murray, Australia. Over 32 paired-day samples of the fishway entrances and exits, 291,483 fish (19 species) were sampled from the large vertical-slot, compared to 183,659 fish (19 species) from the small vertical-slot. Small-bodied fish (<100 mm) dominated the catch (>96%) and large-bodied species were rare at both fishways. Species composition was similar, but species-specific abundances varied widely between fishways. The large vertical-slot successfully passed a broad range of species and sizes, but the passage of several small-bodied (<100 mm in length) species was partially obstructed, whilst passage efficiency was high for all species that entered the small vertical-slot fishway. Variation in head differential and subsequently fishway hydraulics, influenced the number of fish sampled at the entrance of the small vertical-slot and the number of fish sampled at the exit of the large vertical-slot. In unison, however, the fishways facilitated the passage of a diverse migratory fish assemblage across the range of head differential experienced, suggesting the application of paired vertical-slot fishways with differing hydraulic characteristics is likely a viable approach at other low-level estuarine barriers.


## 1. Introduction

Fishways are commonly used to facilitate fish movement past instream barriers and restore connectivity within fragmented river systems (Clay, 1995). A long history of fishway construction and research targeting the upstream migrations of anadromous salmonids has led to significant advances and success in facilitating the passage of these species (Noonan et al., 2012). In contrast, the development of fishways to facilitate upstream passage of fish assemblages is a more recent endeavour and has met with varying success (Calles and Greenberg, 2007; Stuart et al., 2008; Thiem et al., 2013). Importantly, designing single fishways to effectively pass fish assemblages is reliant on providing adequate attraction discharge and space within fishways, whilst also generating internal hydraulics that are surmountable by migrating fish with poor swimming ability. To meet the attraction and internal hydraulic requirements for the passage of disparate species, such fishways are typically low gradient, leading to a large construction footprint and associated cost (Barrett and Mallen-Cooper, 2006).

Estuarine barriers (e.g. barrages), primarily constructed to limit saltwater incursion into the lower reaches of rivers, have been instituted throughout the world, including in India (the Ganges River), Japan (the Nagara River), South Korea (the Nakdong River), the United Kingdom (the River Thames) and Australia (the River Murray). Estuarine barriers may impede the movement of a diverse range of fish species; they represent the first obstructions encountered by diadromous species undertaking upstream migrations, but also impede the upstream movements of displaced freshwater species and euryhaline estuarine and marine species that commonly use the lower reaches of river systems (Stuart and

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Berghuis, 2002; Wasserman et al., 2011). In south eastern Australia, unlike much of the northern hemisphere, the diadromous fish fauna comprises few anadromous species and is dominated by catadromous and amphidromous species (Harris, 1984). These species undertake obligate upstream migrations as small juveniles (typically <100 mm TL), which exhibit inherently weak swimming abilities. Thus, fishways on estuarine barriers in the southern hemisphere must consider the passage of a diversity of species with differing sizes and swimming abilities (Stuart and Mallen-Cooper, 1999; Stuart and Berghuis, 2002).

Estuaries are dynamic environments and pose unique challenges to facilitating fish passage past barriers to movement (Larinier, 2002a). Estuarine water levels are influenced by tides and freshwater discharge and are variable over temporal scales ranging from hours to seasons. As such, the associated head differential (the difference in water level between upstream and downstream) across estuarine barriers is temporally variable, leading to variations in the volume of water discharged by fishways and subsequently, fishway hydraulics (i.e. velocity and turbulence, Rajaratnam et al., 1992). This variation may influence fishway *effectiveness* (sensu Cooke and Hinch, 2013), by dictating attraction of fish to the fishway entrance and passage *efficiency* (here defined as the ability of individuals to successfully pass through a fishway once located). Thus, to achieve fish passage at estuarine barriers, fishway design must consider temporal variability in head differential to ensure attraction and passage efficiency are optimized. Despite estuarine barriers to fish movement being present on most continents they have received less attention than riverine environments in regards to refining fish passage (Larinier, 2002a).

The application of multiple or 'paired' hydraulically distinct fishways that target the passage of different species and size classes of fish is potentially a viable approach for providing fish passage at low-level estuarine barriers (Bunt et al., 1999; Mallen-Cooper and Stuart, 2007). Such approaches may be less expensive than constructing single low-gradient fishways to pass all species (Mallen-Cooper and Stuart, 2007), whilst separating function and optimizing passage for specific fishes may result in cumulatively greater overall passage than achieved via a single one-size-fits-all fishway (Schwalme et al., 1985). Lastly, at barriers where headwater and tailwater, and resulting head diferential are variable, paired fishways may be constructed that operate optimally during different and thus, complementary hydrological conditions. Vertical-slot fishway provide particular promise in such situations as their function is less impacted by variation in head differential than most other fishway designs (e.g. nature-like fishways, Larinier, 2002b).

The objective of the present study was to compare the effectiveness of two hydraulically distinct vertical-slot fishways on an estuarine barrage in south eastern Australia to assess the complementary nature of these fishways as a holistic approach to providing passage for a fish assemblage at a low-level estuarine barrier. Specific objectives were to: i) investigate differences in fishway use (i.e. species composition and abundance); ii) determine the passage efficiency of both fishways, in relation to the species and size classes able to successfully ascend; and iii) determine the influence of head differential on the function of each fishway. Ultimately, this study aims to inform future fishway design and application at other estuarine barriers.

## 2. Methods

### 2.1. Study site

The Murray-Darling Basin (MDB) covers an area of >1 million km$^2$ and is drained by Australia's longest river system. The MDB is regulated by several large dams in the upper reaches, a series of low-level weirs (mostly <3 m) in the mid and lower reaches, and the Murray Barrages near the river mouth (Walker and Thoms, 1993). A total of five low-level (~1.0 m high) tidal barrages (Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere), cumulatively spanning 7.6 km, separate the freshwater Lower Lakes (lakes Alexandrina and Albert) from the remnant Murray estuary (the Coorong) and the Southern Ocean (Fig. 1). Constructed in the 1930s, the barrages maintain a freshwater storage upstream by preventing saltwater intrusion. Tauwitchere Barrage is the longest individual structure, spanning 2.7 km and consisting of 322 gated bays, with a combination of radial gates and pre-cast concrete stop-logs. Under natural conditions, end-of-system discharge was variable with a mean of ~390 m$^3$ s$^{-1}$, but under regulated conditions has been reduced to ~150 m$^3$ s$^{-1}$. Furthermore, cease to flow conditions now occur 40% of the time, compared to 1% under unregulated conditions (CSIRO, 2008).

Water levels both upstream and downstream of the Murray Barrages exhibit hourly–seasonal fluctuations. The large surface area of Lake Alexandrina (~650 km$^2$) results in water level upstream of the barrages being influenced by wind seiche, as well as river discharge. Downstream, water level is influenced by tide, river discharge and wind seiche. In concert, these factors result in temporally variable head differential across the Murray Barrages, which typically ranges 0–0.9 m, with occasional reverse (negative) head differential. The constricted nature of the river mouth, which connects the Coorong and Southern Ocean, means that during times of above average river discharge (e.g. >150 m$^3$ s$^{-1}$), downstream water levels are generally elevated and tidal fluctuations are dampened, resulting in relatively low head differential (i.e. 0–0.5 m). Conversely, during times of below average river discharge, tidal fluctuation is maximised, resulting in variable head differentials, and a greater frequency of periods with relatively high head differential (up to 1.1 m).

More than 60 species of fish have been recorded in the vicinity of the Murray Barrages representing freshwater, diadromous, estuarine and marine life history categories (Eckert and Robinson, 1990; Higham et al., 2002; Potter et al., 2015). A total of 33 species have been recorded attempting to migrate through fishways on the barrages (Zampatti et al., 2010, 2011; Bice et al., 2012), including two catadromous (congolli, *Pseudaphritis urvillii*, and common galaxias, *Galaxias maculatus*) and two anadromous species (short-headed lamprey, *Mordacia mordax*, and pouched lamprey, *Geotria australis*).

### 2.2. Fishways

The first vertical-slot fishway on Tauwitchere Barrage (hereafter the 'large vertical-slot') was constructed in 2004. Due to a paucity of empirical data on fish movement in the region, the design of the fishway was informed by local ecological knowledge (primarily from commercial fishermen), which proposed the importance of upstream movement for the estuarine black bream (*Acanthopagrus butcheri*; max adult length ~600 mm) and juvenile mulloway (*Argyrosomus japonicas*; length range 200–600 mm). As such, the fishway was designed targeting the passage of fish >150 mm TL. The fishway is a concrete channel, rectangular in cross-section, with a total length of 5.5 m, divided into two pools, 2.3 m long × 4.0 m wide, by three pre-cast concrete vertical-slot baffles (Fig. 2a). The design head loss (difference in water level per baffle) is 0.2 m (~0.6 m across entire fishway) and at median headwater levels, the fishway discharges ~0.36 m$^3$ s$^{-1}$, resulting in a maximum velocity of 2.0 m s$^{-1}$ and average turbulence of 95 W m$^{-3}$ (calculated with a Coefficient of Discharge [Cd] of 0.7). The fishway has a flat floor and the hydraulic gradient of 8.7% is created by sills in the base of the vertical-slots. Pool depth is typically 0.8 m. Slot widths are 0.3 m. The fishway was constructed near the middle of the barrage