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Fish passage in the Murray-Darling Basin, Australia: Not just an upstream battle

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Summary Construction of instream barriers, preventing fish from accessing spawning, nursery and feeding habitat, is a major issue impacting fisheries sustainability throughout the world. Since European settlement, development in the Murray-Darling Basin for irrigation and potable water supplies has led to the construction of over 10,000 barriers to fish movement. The Native Fish Strategy listed fish passage as a major driving action and was proactive in progressing cost-effective solutions to help inform large-scale rehabilitation programmes. The strategy identified a list of high-priority barriers for mitigation works based on feedback from jurisdictional agencies. Research initiatives were then implemented, with measurable outcomes, to help address key knowledge gaps. Research demonstrated that a project to restore passage to the Murray River main channel was meeting all ecological and engineering objectives. Follow-on work identified low-cost mechanisms to improve the effectiveness of existing fishways without compromising ecological functionality. The Native Fish Strategy was also explicit in addressing fish passage issues at irrigation infrastructure and wetland regulators. Work to minimise these impacts included quantifying the scale of irrigation-associated infrastructure and also optimising screen designs to be retrofitted to pump systems to prevent fish entrainment. Options to enhance lateral movement were also identified. The objective of this study is to summarise the fish passage issues progressed by the Native Fish Strategy to develop basin-wide solutions to enhance fish passage over the long term.

Key words: *connectivity, fish passage, fishway, migration, Murray-Darling, nonsalmonid.*

Fish in the Murray-Darling Basin

Construction of instream barriers and the subsequent impacts on migration is one of the major threats to freshwater fish diversity worldwide (Lucas & Baras 2000; Lucas *et al.* 2001). Barriers restrict access to spawning grounds and preferred habitats, thus preventing dispersal and recolonisation (Gehrke *et al.* 1995; Pelicice & Agostinho 2008; Welcomme 1995). Disrupting these important ecological processes can lead to large-scale recruitment failure and subsequent fisheries declines (Agostinho *et al.* 2008). Mitigation measures to overcome the impacts of instream barriers often entail large expense, require detailed monitoring programmes and can fail to facilitate large-scale recovery if inappropriately managed (Williams 2008). Fish declines can be reduced or arrested if programmes are appropriately managed, implemented and reported.

The Murray-Darling Basin (MDB) drains an area of ~1,060,000 km^2 or 25% of the Australian continent. Climatic conditions within the basin are arid, semi-arid, or temperate and can be subject to extended periods of drought and flooding. The Murray River, in the southern portion of the basin, is regulated by five tidal barrages, several large dams and 14 low-level weirs (mostly <3 m high) that are operated for irrigation, potable water and navigation along >1000 km of the Murray River (Walker, 1985). Since river development commenced, an estimated 10,000 barriers to fish migration have been constructed in the Murray-Darling Basin.

As has occurred in many other countries, instream barriers have impacted on the abundance and diversity of fish populations by interrupting critical biological processes required to complete essential life-history stages (Harris & Gehrke 1997). Native fish across the Murray-Darling Basin have subsequently declined over the last 100 years (Reid & Harris 1997). Catches of medium-bodied (usually up to 600 mm long) Golden Perch (*Macquaria ambigua*

ambigua), Silver Perch (*Bidyanus bidyanus*) and large-bodied (up to 1400 mm long) Murray Cod (*Maccullochella peelii*) have declined by 51%, 94% and 96%, respectively, in the mid-reaches of the Murray River over a 50-year period (Mallen-Cooper & Brand 2007). In addition, dramatic declines in catch-per-unit-effort of the commercial freshwater fin-fisheries in the states of New South Wales and Victoria led to their closure in 1998 (Reid & Harris 1997). It is generally accepted that many native fish populations of the Murray-Darling require urgent action to facilitate recovery (Koehn & Lintermans 2012; Lintermans *et al.* 2005). If rehabilitation of Murray-Darling Basin fish populations is to be achieved, there is a pressing need to mitigate the impact of barriers to movement through targeted management interventions that enhance and restore fish passage (Mallen-Cooper 2000).

Provision of Fish Passage

To help facilitate population recovery, provision of adequate passage for native fish was included in the Murray-Darling Basin Native Fish Strategy (MDBC 2003). Native fish in the Murray-Darling exhibit complex movement strategies, which involve many different life-history stages. Native fish move between and among different habitats to feed, spawn and colonise new areas (Reynolds 1983). Developing strategies to facilitate fish movements across large spatial scales for many different species and size classes provides a substantial challenge for river managers. For instance, adult Golden Perch, Silver Perch, Murray Cod and Bony Herring move upstream and downstream in spring and summer (Gehrke 1990; O'Connor *et al.* 2005; Zampatti & Leigh 2013), with most of these movements cued by rising discharge (Mallen-Cooper 1999). Immature Golden Perch and Silver Perch migrate upstream in a similar pattern to the adult fish, but can extend into early autumn (Mallen-Cooper 1999). For some species, these movements are cyclic, with return movements occurring later in the same migratory season (Koehn *et al.* 2009).

Fish passage objectives often focus on iconic species of commercial or recreational importance (Mallen-Cooper 1996), and the need for entire fish assemblages to migrate is not often considered in fish passage programmes (Steffensen *et al.* 2013). In the Murray-Darling Basin, small-bodied fish often numerically dominate the migratory population and migrate upstream from midsummer to early autumn, generally during low flows (Baumgartner & Harris 2007; Stuart *et al.* 2008b). The spatial scale of these migrations by small-bodied fish is unclear; however, a major downstream dispersal occurs with drifting eggs and larvae of several species, which is a specific life-history strategy to access nursery areas and reduce interspecific competition at spawning sites (Humphries & King 2004; Humphries *et al.* 1999; Humphries & Lake 2000; Humphries *et al.* 2002). Providing passage for both small and large fish requires specific engineering solutions. The appropriateness of any solution is largely dependent on what direction fish are attempting to move.

Moving Fish Upstream

A need to provide upstream passage opportunities has been accepted globally by biologists and engineers for several hundred years. However, the need for native fish to migrate upstream in the Murray-Darling Basin has been recognised by Aboriginal people for thousands of years (Dargin 1976). Since European settlement, early efforts to facilitate upstream fish passage largely failed due to a lack of understanding of native fish swimming ability coupled with construction of inappropriate fishway designs most suited to North American salmonids (Eicher 1982; Mallen-Cooper & Brand 2007). The North American salmonid fishways were too steep with high velocities, high turbulence and narrow operational ranges (Mallen-Cooper 1996). The failure of these early fishways highlighted a need to identify optimal fishway design criteria specific to native fish. It was apparent that designs developed elsewhere, for other species, could not be directly applied.

To facilitate successful passage for native fish, it was obvious that understanding fish swimming ability would be a useful starting point. Work in New South Wales initially sought to understand the critical swimming performance of adult Golden Perch and Silver Perch and its implications for fishway design (Mallen-Cooper 1994). Adults of these species could successfully negotiate water velocities of 1.8 $m.s^{-1}$ and turbulence of 105 watts per cubic metre ($W.m^3$) [Cd = 0.64], and hence, these criteria were applied to construction of the first vertical-slot fishway at Torrumbarry Weir on the middle reaches of the Murray River (Mallen-Cooper 1996). For Golden and Silver Perch, the fishway was an immediate success (Fig. 1). The Murray-Darling Basin Authority, and relevant jurisdictional agencies, recognised that fish passage obstruction was a substantial issue and that solutions were now available for native fish. A task force was subsequently formed to plan and implement the largest fish passage restoration programme in Australian history, the Sea to Hume project, which aimed to restore passage for the entire migratory fish community in the Murray River, over a distance of 2250 km (Barrett 2004; MDBC 2003).

Moving Fish Downstream

Fish passage requirements within river channels are bidirectional, and there is little point focusing all management efforts on promoting upstream migration if there are limited opportunities for downstream movement (Calles & Greenberg 2009). Large-bodied fish moving downstream can be delayed or even abandon migration if an appropriate migration pathway is not found (O'Connor *et al.* 2005).

Many fish species also have fragile early life stages (i.e. eggs and larvae) that disperse downstream (King 2005; King *et al.* 2005, 2003; Koehn & Harrington 2005). The exact distances traversed during these drifting phases are unknown, but individual fish have been recorded up to 40 days old and could move large distances depending on discharge (Gilligan & Schiller 2003; Stuart & Jones 2006a). In a regulated river system, this downstream drift can be impacted by:

1. Reduced water velocities in weirpools which cause drifting larvae to settle in unfavourable habitats resulting in low survivorship.

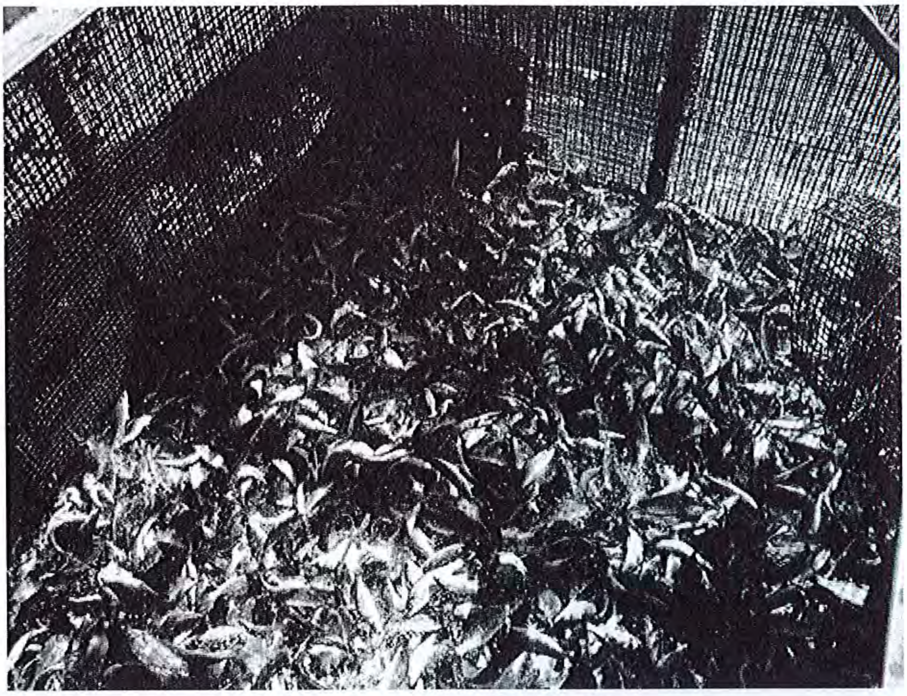

Figure 1. A large catch of juvenile Silver Perch (*Bidyanus bidyanus*) migrating through a fishway at Torrumbarry Weir on the Murray River. Here over 10,000 fish less than 100 mm were collected in a 24 hours period. (Photo: Ivor Stuart).

2 Transport into managed floodplains, off-stream storages or irrigation systems, which either do not drain back to the river or restrict passage back to the river. Larvae could settle in unfavourable habitats, or die through drying of wetlands or irrigation systems.

3 Passage through riverine infrastructure. Research on passage through weirs has shown that undershot weirs can be highly destructive with up to 95% (Golden Perch) and 52% (Murray Cod) experiencing mortality (Baumgartner *et al.* 2011, 2006), but that mortality through overshot weirs is relatively low by comparison (<10%) (Baumgartner *et al.* 2011).

Because it is very difficult to sample or track the movement of larvae, the direct impact of these factors on fish populations is unknown. Some small-bodied fish species thrive in weirpools and managed wetlands but for most native fish species that are declining, these factors may represent a 'sleeper' issue, where there is potentially a great impact on native fish populations that is underestimated without data.

The impact of weir pools, managed floodplains and off-stream storages on the survival of early life stages of native fish can be reduced through water management, although it is not presently being addressed and urgently needs consideration. The impact of undershot gates can be largely addressed through the use of overshot weirs and plunge pools (Baumgartner *et al.* 2011); these have now been specifically provided, or are being built, at: Tyreel Regulator (Gwydir River, construction 2015), Mollee and Gunidgera Weirs (Namoi River, construction 2014), Marebone Weir (Macquarie River), Marebone Break Weir (Macquaire River, construction 2014), Gunningbar Regulator (Macquarie River, proposed construction 2015), Yallakool Creek Regulator (Edward River anabranch), Barbers Creek Weir (Koondrook-Perricoota Forest), Box Creek Weir (Kow Swamp, Murray River anabranch, Vic.; proposed construction 2015), Mullaroo Creek Inlet Regulator (Murray River anabranch, Vic.; proposed construction 2015) and Pike River (Murray River anabranch, SA; proposed construction 2014).

The research on downstream fish passage through infrastructure is a clear example of where applied research has elucidated the problem, as well as developed a solution, which has then had immediate application and rapid uptake. The approach is adaptive management which could be applied to any river system, provided preliminary data are collected on local species in a manner that can be applied directly to engineering projects. A future challenge for downstream fish passage is to use a similar approach to obtain data that can assist with water management in weirpools, floodplains, irrigation systems and offstream storages.

Moving Fish Sideways – Lateral Movements

River–floodplain systems are driven by lateral exchange between main channel systems and adjacent wetlands (Bayley 1995). In many regulated river–floodplain systems throughout the world, lateral exchanges between river and floodplain have been reduced through the construction of regulators to limit flooding (Vilizzi 2012). Increased floodplain development has profound impacts on flow-dependent fish species, which require access to important spawning and nursery habitat to complete essential life-history stages (King *et al.* 2009; Louca *et al.* 2009; Tonkin *et al.* 2008). In many parts of the Murray-Darling Basin, fish species that depended on floodplain habitats are now either rare or locally extinct (Baumgartner *et al.* 2013) despite being historically common (Anderson 1915).

Fish require unrestricted movement from floodplains back to the main stem of rivers in order to avoid stranding (Jones & Stuart 2008). Species such as Golden Perch and Murray Cod will move between the main stem of a river and floodplains during high-discharge periods and will return to channel habitats (Closs *et al.* 2006; Jones 2009, 2007). Facilitating movement of fish back to mainstream habitats can be achieved through the construction of specialist floodplain fishways or potentially by manipulating the river hydrograph (Jones & Stuart 2008).

The need for lateral fish movements has been recognised at fishways in Gunbower Forest, Koondrook-Perricoota Forest, Lindsay–Wallpolla Floodplain, Chowilla Floodplain and Anabranch, as well as other anabranch floodplain sites along the Murray River, including Pike River floodplain and Katarapko Creek in South Australia. Each of these sites has unique fishway designs or unique applications, due to differing fish assemblages, ecological objectives and hydrology.

Improving lateral connectivity not only benefits native species, but also facilitates the movement of non-native species utilising floodplain habitats (Jones & Stuart 2009; Stuart & Jones 2006b). Generalist species, such as Common Carp (*Cyprinus carpio*), are prolific within the MDB, and research has demonstrated that spawning and recruitment are stimulated by providing lateral access to resource rich (i.e. food and habitat) floodplains (Bice & Zampatti 2011; Conallin *et al.* 2012; Jones & Stuart 2009; Stuart & Jones 2006a). Carp will inhabit floodplain habitats when inundated, with some individuals travelling large distances (>200 km) to gain access to these resources (Jones & Stuart 2009; Stuart & Jones 2006a). Consequently, improving lateral connectivity needs to be balanced to ensure that anticipated benefits for native species outweigh potential recruitment of non-native pest species.

Fish Passage Task Force – Solutions Need to be Coordinated

Establishment of a coordinating committee is the critical first step in any fish migration construction programme because it provides an important link between science and stakeholders (Anon 2006). Committees provide overall direction, establish priorities and standardise biological design criteria. Well-established committees hold regular meetings and advocate adaptive management principles to regularly revise design criteria based on new science.

A technical advisory group (Fish Passage Task Force; FPTF) was formed to guide the restoration of fish passage at several low-head weirs (each <4 m high), along the entire length of the Murray River between the Murray mouth and Hume Dam (Barrett & Mallen-Cooper 2006). The FPTF brought together scientists and engineers with the funding agency and the asset owners/operators. The group was chartered to ensure the most effective cost and function balance and to further ensure that the designs were continually optimised for the entire migratory fish assemblage.

The migratory fish assemblage was defined as fish from 50 to 1000 mm long, presenting design, engineering and operational challenges at an unprecedented scale. Passing such a diverse size range of fish required specific fishway design criteria. Data on the swimming ability of small-bodied coastal fish species provided accurate criteria for water velocity (maximum 1.4 m/s) and turbulence (45 W/m^3) (Barrett & Mallen-Cooper 2006; Stuart & Mallen-Cooper 1999), and these were combined with large pools (3 m long by 2 m wide by 1.5 m deep) for the passage of large-bodied fish. The fishways were also designed to operate over a wide range of river flows (>99% of the time for large fish and >95% of the time for small fish; noting that the weirs are removed during high flows). The first of the new vertical-slot fishways passed fish from 50 to 1000 mm long, meeting the original objective; but assessment revealed new data on fish movement. Much smaller fish (25–50 mm long) were trying to migrate in high numbers, and few could ascend the fishway (Baumgartner *et al.* 2010). These small fish could, however, pass when the fishway was experimentally operated as a lock (Stuart *et al.* 2008a), which provided the impetus for a novel approach.

The adaptive nature of the construction programme allowed the FPTF to incorporate this new knowledge into a substantial design change for the final six fishways. These were designed with a 'father–son' concept, where the father was a high-flow, vertical-slot fishway (slope 1v:20 h, water velocity 1.8 m/s, turbulence 105 W/m^3 (Cd = 0.64)) for large-bodied fish. The son fishway, was a specially designed small fish lock with flows that could be manipulated to any target range by operating sluice gates. A fish lock was selected on the basis that biological data strongly supported the ability of these designs to provide passage for small-bodied fish (Baumgartner & Harris 2007; Stuart *et al.* 2008a). The fishways have adjacent entrances, but high water velocities in the high-flow vertical-slot fishway enable only large fish to enter whilst providing attraction for small fish, which then enter the adjacent low-flow fish lock.

The new vertical-slot/lock combination fishways should enable passage of fish from 12 to 1000 mm long. Separating ecological function, by moving large and small fish separately, enabled a fishway design that passes the whole migratory fish community. Capital cost of the new design was estimated to be the same as the previous design, but construction has shown that the added complexity of the fish lock has higher capital, operating and maintenance costs. Upon completion of the Murray fishways construction programme, through the coordinated activities of the FPTF, fish from a range of sizes and life-history stages will potentially be able to move along 2000 km of the Murray River main channel for the first time in 90 years.

Innovations in Upstream Movement Techniques

A major factor in the capital cost of vertical-slot fishways is the channel gradient (slope), which determines total fishway length (Mallen-Cooper *et al.* 2008). Concern over the increasing construction costs of the Sea to Hume fishways drove a need to develop techniques to maintain ecological functionality without the need for overly conservative biological design criteria. Three approaches were investigated as follows: (i) providing roughness in the high-velocity zone of the vertical-slot baffle, using bristles or steel baffles, to reduce localised velocities for small-bodied fish, (ii) separating ecological function and providing a small Denil fishway for small-bodied fish whilst passing large fish in a large steeper fishway and (iii) manipulating turbulence within the fishway pool. These options were investigated on the Murray River in a series of controlled field experiments (Barrett & Mallen-Cooper 2006; Mallen-Cooper 1999).

Providing roughness in the high-velocity area in the slot of the baffle, surprisingly, provided little benefit. The small Denil fishway was also very species selective, effectively passing some species but excluding others, whilst being very sensitive to water-level changes. These results led to investigating turbulence. Turbulence is frequently identified as the major factor limiting the passage of small-bodied species and can be manipulated in a fishway pool either by: (i) improving dissipation of energy in the pool or (ii) reducing the amount of energy entering the pool (Liu *et al.* 2006; Mallen-Cooper 2005; Tarrade *et al.* 2008).

The FPTF identified a number of innovations of the vertical-slot fishway design that could help increase gradient whilst retaining, or improving turbulence and functionality. These options were modelled in three dimensions using computational fluid dynamics (CFD) (Fig. 2) to identify the most promising designs. The solutions identified with the most potential were as follows: (i) adding wall roughness to improve energy dissipation and create a low-velocity barrier along the fishway wall for fish to move and (ii) positioning sills (or block-outs) in the middle of the vertical-slot baffle, to reduce overall discharge whilst enabling both pelagic and benthic species to pass.

Unmodified, high-turbulence (e.g. 105 W/m^3, Cd = 0.64), vertical-slot fishways on a gradient of 1v:20 h provided very poor passage of all small-bodied fish species (25–90 mm long), which is expected as these fishways are generally designed for fish >100 mm long in Australia (Mallen-Cooper 2005). Adding middle sills and reducing turbulence (e.g. 30 W/m^3), whilst keeping the same fishway gradient, greatly improved functionality with hundreds of small-bodied fish passing through two pools of the fishway in 30 min (Mallen-Cooper *et al.* 2008). Adding middle sills increased passage of small-bodied fish 6 to 13 times compared with an unmodified fishway, and adding wall roughness increased passage up to four times (Mallen-Cooper *et al.* 2008). The work was the first time that very small Australian fish were observed successfully using a steep (1v:20 h) fishway, and the results have already been applied to numerous projects: in the basin these include (Darling River at Burtundy Weir and Weir 32; Murrumbidgee River at Beavers Creek Weir; Lachlan River at Booligal Weir; Macquarie River at Marebone Weir, Marebone Break Weir [fishway to be constructed in 2014], Gunningbar Creek Offtake [fishway to be constructed in 2015] Gwydir River at Tyreel Weir and Tyreel Regulator [both fishways to be constructed in 2015–16]; in coastal streams these include the Nepean River [11 new fishways completed] near Sydney and the Yarra River (Dights Falls, completed in 2012) in Melbourne; and in experimental fishways in Laos (South East Asia). This provides a good example of rapid and widespread uptake of applied research as well as having a 'ripple effect' across geographical boundaries beyond the scope of the original project. The long-term implications of this work are the construction of less-expensive fishways, which have improved ecological functionality. It could also be extended to improve the operation of existing, high-slope fishways, which could benefit from decreased turbulence to improve ecological functionality.

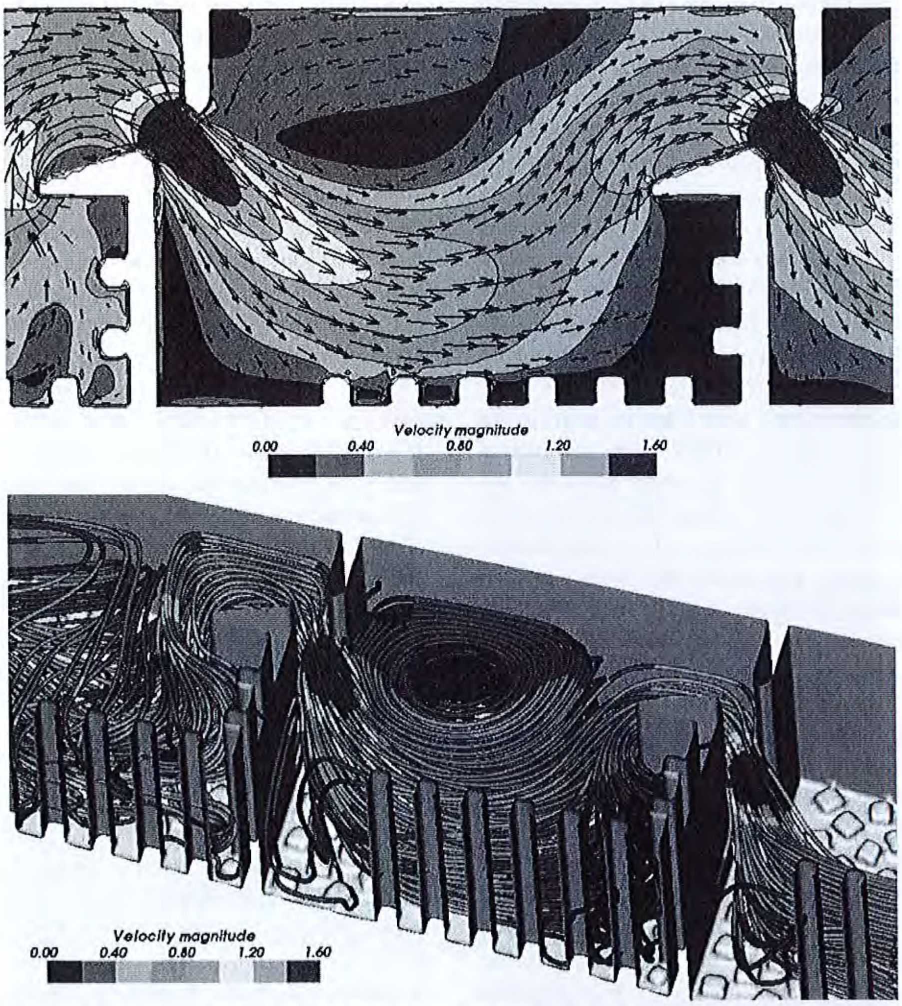

Figure 2. Computer modelling (CFD) of a vertical-slot fishway with wall roughness (projections along wall; modelling by WorleyParsons). This type of modelling was used to select designs to field test.

Passage at the Murray Mouth and Barrages

A critical aspect of many river systems is the freshwater–saltwater interface. These estuarine zones are often biodiversity hot spots and can constitute spawning and/or nursery habitats for diadromous fishes. The Coorong estuary lies at the terminus of the Murray-Darling river system in South Australia. The estuary and lower Murray River support a highly diverse fish assemblage (Wedderburn *et al.* 2012; Zampatti *et al.* 2010a) with a broad range of life-history requirements, but passage between estuarine and freshwater habitats was blocked in the 1940s by a series of tidal barrages 7.6 km long. Despite a relatively low-head differential (<1 m) across the barrages, fish passage was not originally incorporated into barrage construction.

The Sea to Hume Dam programme acknowledged the need to facilitate passage between the brackish–marine waters of the Coorong and the freshwater lower lakes for estuarine, diadromous and displaced freshwater species. Due to a lack of biological information, commercial fishers in the region were consulted on optimal fishway design criteria. The fishers indicated the need to facilitate passage for large-bodied estuarine species such as Mulloway (*Argyrosomus japonicus*) and Black Bream (*Acanthopagrus butcheri*), displaced freshwater species (e.g. Golden Perch) and catadromous species (e.g. Congolli, *Pseudaphritis urvillii*). Subsequently, two vertical-slot fishways were constructed at the Goolwa and Tauwitchere barrages with internal hydraulics that would facilitate the passage of fish ranging 150–1000 mm. To complement the vertical-slot fishways, a rock-ramp fishway was constructed at Tauwitchere to facilitate the passage of fish ranging 40–150 mm.

Preliminary assessments indicated that large-bodied estuarine fish species did not utilise the fishways despite being present in the vicinity of the fishway entrances (Baumgartner *et al.* 2007b; Stuart *et al.* 2005). The large vertical-slot fishways were, however, effective at facilitating the upstream passage of displaced freshwater species such as Golden Perch (Jennings *et al.* 2008). Over 98% (54,446 individuals) of fish collected across all barrage fishways and 96% (103,621 individuals) collected at the Tauwitchere vertical-slot fishway were small-bodied species <100 mm long (Jennings *et al.* 2008; Stuart *et al.* 2005). Many of these individuals were collected attempting to ascend the vertical-slot fishways but were unable due to unsuitable fishway hydraulics (high velocity and turbulence). Nevertheless, on rare occasions, these fish were able to move upstream during periods of low or negative head differential between the lower lakes and the Coorong (Jennings *et al.* 2008). Subsequently, two additional vertical-slot fishways with internal hydraulics appropriate for the swimming abilities of small-bodied fish were constructed at Tauwitchere barrage and the Hunters Creek causeway (Table 1). Assessment of these fishways indicated the effective passage of high species richness (~20 species) and high abundances of catadromous and freshwater species ranging from 20 to 300 mm (Zampatti *et al.* 2010b).

Although passage of large-bodied estuarine species (e.g. Black Bream and Mulloway) was considered a high priority at the Murray barrages, passage of these species has been negligible through the existing fishways. Investigation of Black Bream movement using acoustic tagging techniques has demonstrated upstream movement of Black Bream from the Coorong into the lower lakes when there is negative head differential between the Coorong and the lakes (authors unpublished data). Operation of the barrages, however, is geared to minimise such events in order to prevent increased salinities in the lower lakes. Generally, there is no gradient in salinity between the lower lakes and the Coorong; instead, there is an abrupt transition between fresh and brackish/marine salinities. The impact that changes in such physiochemical signals have on the upstream movements of these species is uncertain.

In the Murray-Darling Basin, connectivity between the Southern Ocean, estuary and the freshwater environments of the lower lakes and Murray River is imperative for at least five species of diadromous fishes, namely anadromous Short-headed and Pouched Lamprey (*Mordacia mordax* and *Geotria australis*) and catadromous Common Galaxias (*Galaxias maculatus*), Congolli and Short-finned Eel (*Anguilla australis*). The original intent of the Sea to Hume Dam Fish Passage programme was to construct a number of experimental fishways at the Murray barrages use assessment results to inform additional fishways in the region. The need for several additional fishways at the Murray barrages was seen as a priority in South Australian Government's Coorong, Lower Lakes and Murray Mouth Long Term Plan. Additional fishways are now imminent at the Goolwa, Mundoo, Ewe Island, Boundary Creek and Tauwitchere barrages and will include low-velocity, low-turbulence vertical-slot fishways and novel tidal fish locks.

Fish Passage in the Darling River

Fish passage in the Darling River system remains a priority but presents substantial challenges (Boys 2007). A series of low-head weirs along the entire length of the river prevent longitudinal fish movement along the main channel and into tributary streams (Boys 2007). The Darling River has a highly variable hydrology, even by Australian standards, with regular drought and irregular broad-scale slow-moving floods (Harris *et al.* 1992b). Compared with the southern basin, the northern basin has semi-arid to arid rivers, a different climate and geography. The Darling River is semi-arid, with flow for 95% of the time and median and maximum zero-flow spells of 13 and 131 days (Bourke; 1943–1991), whilst the Warrego River is arid, with flow for only 57% of the time and median and maximum zero-flow spells of 64 and 302 days (Cunnamulla; 1992–2009) (Nichols *et al.* 2012). High flows are more variable than the southern half of the basin but generally occur annually in wet decades and between 3 and 6 years in dry decades.

The difference in hydrology has resulted in a fish assemblage which strongly contrasts with southern sections. Seven species found in the southern basin (Trout Cod, Macquarie Perch (*Macquaria australasica*), Flat-headed Galaxias (*Galaxias rostratus*), Southern Pygmy Perch (*Nannoperca australis*), two-spined blackfish (*Gadopsis bispinosis*), short-headed lamprey, pouched lamprey and Common Galaxias are not found in the north, whilst Spangled Perch (*Leiopother-*

Table 1. Summary of fishway design specifications on the Murray River.

Site	Weir constructed	Year of fishway construction or due completion	Fishway design	Floor slope	Maximum head differential (m)	No. of pools or Denil channels	No. of exits
Coorong and Murray mouth							
Goolwa	1940	2003	Large vertical-slot	1:20*	1	3	1
		Funded, ~2015	Large vertical-slot	1:20*	1	3	1
		Funded, ~2015	Fish lock	N/A	1		1
Tauwitchere	1940	2004	Large vertical-slot	1:20*	1	2	1
		2008	Small vertical-slot	1:20*	1	15	3†
		2004	Rock ramp	1:20*	1		1
		Funded, ~2015	Trapezoidal weirs	1:20*	1		1
Mundoo	1940	Funded, ~2015	Small vertical-slot	1:20*	1	15	3†
Ewe Island	1940	Funded, ~2015	Dual vertical-slot	1:20*	1	4	1
Boundary Creek	1940	Funded, ~2015	Small vertical-slot	1:20*	1	15	3†
Hunters Creek	1940		Small vertical-slot	1:22*	0.5	4	1
Main channel							
Lock 1	1922	2009	Vertical-slot	1:32	2.8	27	4‡
Lock 2	1928	2013	Vertical-slot Fish lock	1:23	3.3	20	4‡
Lock 3	1925	2011	Vertical-slot Small fish lock	1:23	3.5	24	5‡
Lock 4	1929	2013	Vertical-slot Small fish lock	1:23	3.2	22	5‡
Lock 5	1927	2012	Vertical-slot Small fish lock	1:23	3.13	21	5‡
Lock 6	1930	1930	Submerged orifice§, (decommissioned 2010)	1:6	2.95	9	1
		2010	Vertical-slot Small fish lock	1:23		20	5‡
Lock 7	1934	2004	Vertical-slot	1:32	1.9	18	5‡
Lock 8	1935	2003	Vertical-slot	1:32	2.6	26	5‡
Lock 9	1926	2005	Vertical-slot	1:32	2.8	27	5‡
Lock 10	1929	2006	Vertical-slot	1:32	3.3	34	1
			Denil	1:6		1	1
Lock 11	1927	2013	Denil	1:8	3.87	6	1
Lock 15	1937	1937	Submerged orifice§ (converted to Denil 2002)	1:9	4.5	15	1
		2002	Denil	1:6.6	4.5	5	1
		2013	Denil extension	1:6.6	5.0	7	3†
		2013	Small fish lock		5.0		
Lock 26	1928	1992	Vertical-slot	1:18	6.5	39	1
Yarrawonga	1939	1996	Fish lock	N/A	10		1

*Hydraulic gradient can be reduced at high tide levels.
†Multiple exits enable the fishway to operate at varying headwater levels.
‡Multiple exits provide additional flow through the fishway at high tailwater levels.
§Old ineffective design; too steep and turbulent, based on salmonid design criteria. Passed small numbers of large native fish.

apon unicolor) and Hyrtl's Tandan (*Neosilurus hyrtlii*) are only found in the northern basin.

Prior to the construction of weirs along these rivers, population recovery following droughts would have been rapid as there were few, if any, natural barriers in the lowlands (Nichols *et al.* 2012). Localised small flows would have reconnected waterholes and enabled fish to recolonise. At present, these dispersal movements are restricted to large floods when the weirs are submerged. Hence, opportunities to recolonise have been reduced since the construction of weirs. If a particular species is cued to disperse at low to moderate flows and not in floods, then movement opportunities are further reduced and the impacts on the population are potentially much greater.

Several fishways have been built on the lower Darling River, (Nichols *et al.* 2012), which facilitate movements of large- to small-bodied species. Passage at the other structures, without functional fishways, is only possible during irregular flooding (Harris *et al.* 1992a; Mallen-Cooper & Edwards 1990). Relying on natural flooding to maintain fish passage is problematic because opportunities occur infrequently and over a short time period. These irregular passage opportunities are also more advantageous for large-bodied species because river discharges are often too high to suit the swimming ability of small-bodied fish. A logical extension of the Sea to Hume programme would be to reinstate fish passage on all major weirs on the Darling River main channel (Fig. 3). Concept fishway drawings for most structures have been prepared, and progressing these to detailed design and construction would restore fish passage to both major waterways in the Murray-Darling Basin (Nichols *et al.* 2012).

Interactions with Irrigation Infrastructure

A unique fish passage issue is entrainment or diversion into irrigation infrastructure (King & O'Connor 2007). Work in North America has demonstrated that many migrating salmonids are removed from waterways when water is abstracted irrigation and potable (Post *et al.* 2006; Prince 1923). The significance of this issue is profound with a high percentage of salmonid recruitment being affected in the Columbia River Basin (McMichael *et al.* 2004). The issue is considered large enough to establish dedicated task forces and coordinating committees to implement on-ground works programmes to protect migrating fish. Despite global recognition of this potential issue, fish passage at irrigation offtakes is rarely considered in Australia.

Each year, a large proportion of annual run-off is diverted for irrigation use in the Murray-Darling Basin (Crabb 1997). Most water infrastructure throughout the basin aims to enhance water delivery for irrigation. There are two main types of irrigation infrastructure which influence fish welfare. Firstly, water extraction at diversion weirs into irrigation canals can be responsible for removing many fish of differing life-history stages (King & O'Connor 2007). Adult fish relying on flow as a cue for downstream or lateral migrations may inadvertently move with water into irrigation systems. Many eggs and larvae may be also removed from river channels if water is removed during the spawning season (Baumgartner *et al.* 2007a). Irrigation canals are mostly terminal systems, and any fish inadvertently trapped will have limited opportunities to return (King & O'Connor 2007). Secondly, fish may be directly removed by pumping systems. In northern parts of the Murray-Darling Basin, water is extracted into large holding dams and then reregulated onto crops when required (Baumgartner *et al.* 2009). High-volume pumps are used to extract water, and in some instances, fish are entrained into pump systems from source rivers and are unable to return. Pumping systems on the Namoi River have been shown to extract hundreds of fish per day (Baumgartner *et al.* 2009). Whilst some fish died, many others survived only to be transported into irrigation holding dams.

Fish screens are commonly used to mitigate the impact of irrigation systems on fish in North America (Gale *et al.* 2008; Kepshire 2000; McMichael *et al.* 2004; Mesa *et al.* 2009). Screens are highly effective when designed and installed correctly because fish are either prevented from entering irrigation systems or extracted fish are returned to the source river (CDFG 2000; NMFS 1997; Norlund 1996). Over the past five decades, over 50% of all irrigation diversions have been retrofitted with screens in Oregon, USA (Kepshire 2000). Several factors contribute to the success of any fish screen installation. The mesh size must be consistent

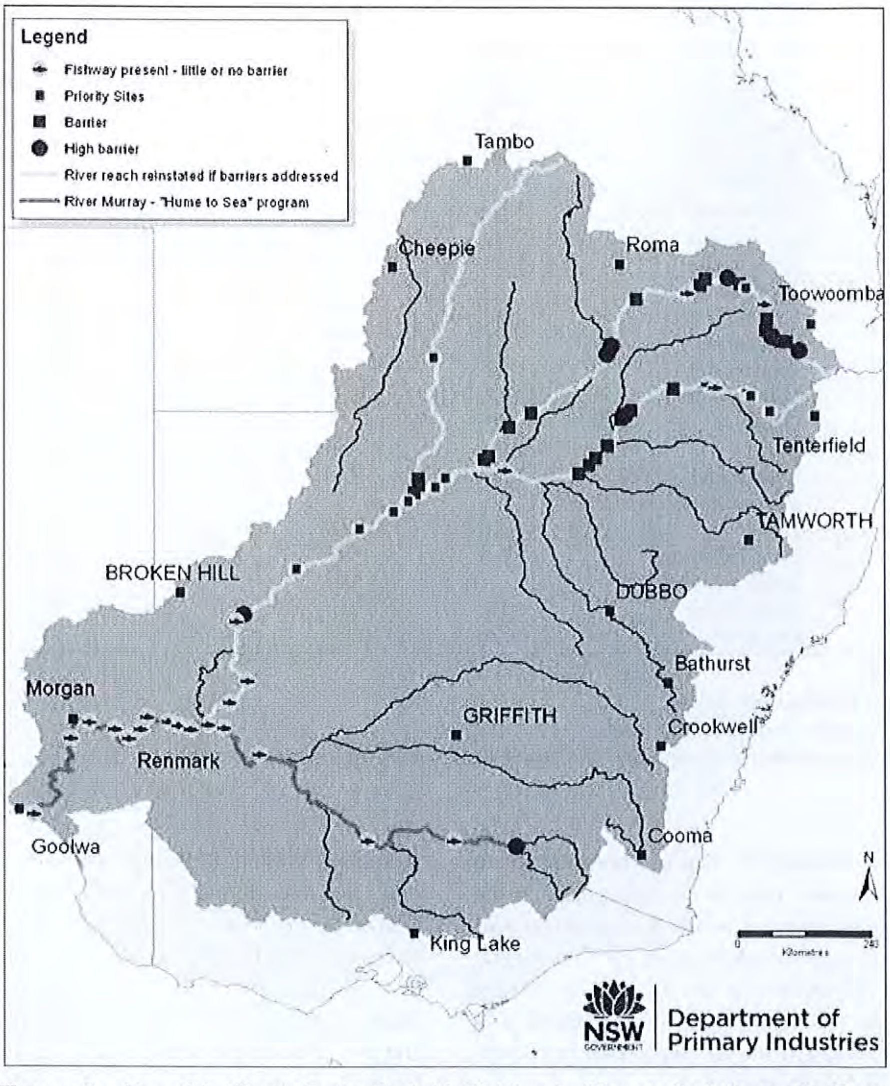

Figure 3. Map of the Murray-Darling Basin highlighting the 'Hume to Sea' sites on the Murray River and the major tributaries of the Darling River where fish barriers and fishways are present. The northern region of the basin remains a challenge for broad-scale application of fish passage; however, the benefits are extensive with 4200 km of river opened up for fish migration by providing passage at 42 barriers along the main stem of these rivers.

with the target fish community, so advance knowledge of the community being protected is needed to advance sustainable solutions. Expected flow at the diversion or pump is critical to understand to ensure irrigator entitlements are not compromised (Baumgartner & Boys 2012). Construction of a fish screen may effectively prevent fish entrainment but will be ultimately ineffective if fish become impinged on the screen (Peake 2004). Impingement can contribute to high mortality rates and can further foul a screen resulting in costly maintenance. Two critical factors in screen design are approach and sweeping velocity (Kepshire 2000). Approach velocity is the speed of water in the river as it approaches (perpendicular to) the screen. It is generally higher closer to the screen and fish that cannot escape will ultimately become impinged. Sweeping velocity is the flow of water across (parallel to) the screen itself. Provision of a high sweeping velocity can minimise impingement and also self-clean the screen and prevent fouling. The ability for fish to cope with either of these critical design criteria is dependent on species, size and life-history stage.

To provide solutions which benefit an entire fish community requires careful thought and planning. To effectively mitigate the impacts of irrigation infrastructure on all species and life-history stages, an extremely small mesh size is required (Boys *et al.* in press). The ability of fish to avoid screen contact is related to size and swimming ability. Understanding fish community composition is therefore critical to develop a functional and cost-effective screening solution (Baumgartner & Boys 2012). Further work on the ecology of fish movements, particularly larvae, would also identify optimum season and times when water extraction minimises impacts on native fish. At present, scientific data generated from the Native Fish Strategy have provided sufficient justification for developing screening programmes for irrigation offtakes and pumps. However, acceptance by industry and coordination are essential to ensure uptake of concepts and techniques in a manner which will benefit all native fish.

Table 2. List of priority sites for fish passage works in the Murray-Darling Basin, developed by the Fish Passage Task Force.

Barrier name	River	State	Fishway completed
Steven's Weir	Edwards River	NSW	Yes
Menindee Lakes Main Weir	Darling River	NSW	No
Caseys Weir	Broken River	Vic	Yes
Boomi Weir	Macintyre River	Qld	No
Cunnamulla Weir	Warrego River	Qld	No
Gogeldrie Weir	Murrumbidgee River	NSW	No
Redbank Weir	Murrumbidgee River	NSW	No
Kerang Weir	Loddon River	Vic	Yes but repairs required
Brewarrina Weir	Barwon River	NSW	Yes
Gowangardie Weir	Broken River	Vic	No
Gulf Regulator	Smith Creek Barmah Lakes	Vic	No
Loudoun Weir	Condamine River	Qld	Yes
Mullaroo control structure	Lindsay River/ Mullaroo Ck	Vic	Detail design
Tea Garden Creek Weir	Ovens River	Vic	No
Bourke Weir	Darling River	NSW	No
Walgett Weir	Barwon River	NSW	No
Neil Turner Weir	Maranoa River	Qld	No
Eulo Weir	Paroo River	Qld	No

Future Challenges

The past decade has seen substantial advances in fish passage knowledge to help rehabilitate Murray-Darling fish populations. These advances were only possible due to an unprecedented amount of biological research to fill knowledge gaps about the basic life history of native fish. The Native Fish Strategy, with a catchment-based, cross-jurisdictional charter, provided a framework for communication among researchers and managers that enabled cross-fertilisation of ideas and rapid adoption of research findings, and the fish passage programme used this advantage to the fullest.

Establishing the FPTF was central to progressing fish passage solutions at a basin-wide scale. Without central oversight, there is a risk that setting priorities for new fishways, as well as optimising design, operation and maintenance of existing facilities will not be integrated. In the absence of a centralised representative body, individual managers within jurisdictional governments will be responsible for ensuring that fish passage is considered across a wide geographical range including the development of future fish passage priority sites (Table 2). This will be difficult to achieve given that jurisdictional governments do not have uniform ecological objectives.

Critical Lessons

1. river infrastructure must be designed with solid information on local fish ecology, river hydrology and include clear operations and maintenance plans;
2. the setting of each fishway is unique, despite often having the same elements and design criteria, and hence they require review by engineers and scientists,
3. experimental research provides the foundation of new designs in fish passage and
4. monitoring and assessment are essential, firstly to ensure that a fish passage project is operating as intended and secondly to provide ecological insights that refine future fishway designs and operation. A central coordinating committee

proved to be the most productive method to facilitate these processes.

The Sea to Hume project is a flagship programme in the MDB, but it still faces some unresolved challenges. Among these is integration of regulated river flows into fishway management. Water demand changes on a daily basis and integrating flows to operate fishways and stimulate fish migration remains elusive. To synergise these functions, we suggest implementation of flow delivery strategies that suit both consumptive water use and fish ecology, which has recently been successfully trialled in a tributary of the Murray River (Baumgartner *et al.* 2013). By delivering water in a manner that has two complementary outcomes, benefits will be maximised across a more diverse range of end-users. Incorporating fish into annual flow planning would be a substantial mechanism to maximise ecological outcomes.

The success of the Murray River vertical-slot fishways, on low-head weirs, must be judged against progress on fish passage at high-head structures. In the Murray-Darling Basin, few fish locks have been built and assessed, but those that have been evaluated have been hampered by long-term operational problems (Baumgartner & Harris 2007). Hence, designers and fish passage experts still need to demonstrate operational reliability and value for money for fish locks.

Downstream passage of fish into irrigation areas, off-stream storages and managed floodplains, as well as passage of larvae in weirpools, remains largely unresolved. These areas require targeted research, monitoring and adaptive management. They have potential for significant gains in rehabilitating native fish populations. As a priority, we recommend a pilot programme of screening a small or medium gravity-fed irrigation offtake, with biological assessment.

Advances over the past decade have helped to facilitate upstream, downstream and lateral migrations of fish throughout the MDB. Importantly, new ecological data were integrated in an adaptive manner and fishway designs changed, and some irrigation pumps and weirs modified to suit the needs of native fish. All solutions focused on the fish community, and not only recreationally important species. A legacy of the Native Fish Strategy fish passage programme will be a major Australian river reopened for fish migration, providing a significant advancement in the long-term recovery of native fish populations. Another legacy is the professional networks that have developed and which appreciate that cross-jurisdictional approaches provide greater benefits for the whole basin. Over a century of decline in native fish populations will not be reversed in a decade. Without an active and well-resourced Native Fish Strategy or similar programme with a central coordinating committee, implementation of fish passage solutions across partner states will prove difficult, and barriers to fish passage will remain a major impediment to the long-term recovery of native fish species.

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