Native fish losses due to water extraction in Australian rivers: Evidence, impacts and a solution in modern fish- and farm-friendly screens

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Craig A. Boys and Thomas S. Rayner are Senior Freshwater Fish Ecologists with the New South Wales Department of Primary Industries (Port Stephens Fisheries Institute, Private Bag 1, Nelson Bay, NSW 2315, Australia; Tel: +61 2 49163851; Email: craig.boys@dpi.nsw.gov.au and tom.rayner@dpi.nsw.gov.au), Lee J. Baumgartner is a Professor of Fisheries and Management and Katherine E. Doyle is a Fisheries and Hydropower Researcher (both at Institute for Land, Water and Society, Charles Sturt University, PO Box 789, Albury, NSW 2640, Australia; Tel: +61 2 60519271; Email: lbbaumgartner@csu.edu.au and kadoyle@csu.edu.au). This review consolidates all the historic and contemporary evidence on fish losses at Australian river diversions and outlines how a new Australian best-practice in diversion screening can be a big win for the environment and the prosperity of regional towns.

Summary The diversion of water from rivers removes millions of fish from Australian waterways each year. Modern diversion screens are available that can reduce fish losses by 90% and stop debris entering irrigation systems. Uptake of this technology in the United States has protected fish and infrastructure. However, application in Australia has been poor and both the problem and its solution continue to be overlooked. To address this, we summarise multiple lines of evidence on fish losses in Australia and propose a way forward. Large losses of fish at diversions have been reported for close to a century, providing compelling evidence of population-scale impacts on native fish. We discuss the solution, outlining the progress being made to bring modern screening technology to Australia, including a social learning framework to improve how water is diverted and focussing on collaboration between the fisheries, agriculture and engineering sectors, and underpinned by science. We conclude that uptake of modern screens will rely on dialogue moving past whether a problem or solution exists, to the following: how screening can be better integrated with water and environmental management; where investment should be prioritised; and how screening could be funded. If Australia gets this right, substantial benefits can be realised, saving millions of native fish every year, bolstering native fish recovery programmes, reducing ongoing costs for water users and enhancing the economic and social value in regional areas by boosting manufacturing, service industries, tourism and recreational fisheries.

Key words: fish losses, fish screen, irrigation diversions, Murray–Darling Basin, native fish recovery.

Introduction

Meeting unprecedented global demand for freshwater is an environmental challenge (Postel 2000; Baumgartner et al. 2019). Over 50% of flow is extracted from rivers worldwide, with 70% of this being for irrigated agriculture (Grafton 2019). Other uses include mining, manufacturing and municipal water supply. Water extraction alters river hydrology and habitats, and degrades freshwater ecosystems (Kingsford 2000). It also removes fish and other aquatic life from rivers – they are sucked into pumps or swept down channels, often stranded in significant numbers (Moyle & Israel 2005; Baumgartner & Boys 2012). With the water goes debris which can clog inline filters, sprinkler nozzles, siphon

Implications for managers

• Millions of native fish are lost from Australian rivers every year. They are sucked into pumps and diverted into channels, and this is likely having a significant impact on populations
• These losses are unnecessary. Modern screens are available and have been tailored to Australian conditions to stop fish and debris entering diversions and deliver environmental and socio-economic benefits to business and towns.

• A social learning programme ‘Fish Screens Australia’ has been established to showcase modern screens, provide best-practice guidance to industry and facilitate a collaborative approach to modernising water diversion practices in Australia.
• Success will be dependent on dialogue moving beyond whether a problem or solution exists, to how screening can be better integrated with water and environmental management, and where investment should be prioritised and how to pay for it.
tubes, and other discharge outlets, causing increased costs for water users and reduced water efficiency (Msibi et al. 2014, Fig. 1).

These problems arise because in many cases gravity-fed water diversions do not have a screen – a physical barrier to exclude fish and debris from diverted water. Furthermore, pump diversions typically only have a coarse-mesh (known as a ‘trash rack’) fitted to the intake (Fig. 2). These trash racks are poor performers – they may stop large items like branches entering pumps, but water enters the diversion too fast, passing through gaps in the mesh that are too big to exclude small items like vegetation, fish and other aquatic animals.Velocities in front of a typical trash rack can be as high as a few metres per second, exceeding the swimming capabilities of larval, juvenile and adult fish (Kopf et al. 2014; Watson et al. in review). Therefore, smaller fish and debris may be sucked into the pump, while larger ones may be impinged on the trash rack. Any blockage is held in place by the high velocity and an increase in head loss at the diversion can disrupt supply and pump performance.

Modern diversion screens fix these problems (Fig. 3). They are ‘fish-friendly’, reducing the injury and mortality at diversions by over 90% (Walters et al. 2012; Boys et al. 2013a; Poletto et al. 2015). They are also ‘farm-friendly’ because they reduce debris entrainment, reducing operational costs whilst increasing water-use efficiency and crop yields through more even irrigation coverage (Boys & Rayner 2020). This is achieved by having a large surface area, fine mesh (often 1–3 mm), internal hydraulic baffling and being self-cleaning with a physical brush or a jet of air or water. These features spread the velocity across the entire screen face and greatly reduce the velocity at any one point, without affecting the volume of water being extracted. Fishes can pass very close to a modern screen without being sucked into the diversion or impinged on the screen. Because of the finer mesh and lower velocity, ‘plugging’ of screen holes is reduced and any debris held lightly on the screen face is periodically brushed or washed away. Screen orientation with respect to river flow can also assist in bypassing fish and debris.

Adoption of modern screening technologies has varied spatially at the global scale (Figure S1). In the United States, the loss of fish at unscreened diversions has been recognised since the 1920s (Prince 1923, Brannon 1929 cited in McMichael et al. 2004), and today ‘fish-friendly’ screens are readily available. These modern screen designs have evolved through decades of product development by fisheries scientists, engineers, farmers and natural resource managers. As a result, diversion screening is now one of the most commonly applied fisheries management practices in North America (Moyle & Israel 2005) and uptake in other countries (such as New Zealand since the 1980s) has followed.

Meanwhile, the promotion and application of modern screens in Australia have been poor (Blackley 2003; Baumgartner & Boys 2012). Most water diversions in Australia are either unscreened or screened insufficiently to prevent fish entrainment (Baumgartner & Boys 2012). The low rate of uptake of modern screens in Australia appears to be driven by a series of concerns and misconceptions. These include the following: a poor recognition of fish losses and the impact on broader fish populations; a lack of awareness of modern screening technologies; and, a reluctance to impose an additional capital cost on water users or the public.

This paper sets out to progress modern diversion screening in Australia, using the Murray–Darling Basin (MDB) as a case study and: (i) consolidating the historical and contemporary evidence of fish losses; (ii) explaining how modern ‘fish-friendly’ screens are being tailored to complement river restoration programmes and stimulate regional economies; (iii) outlining a collaborative framework for promoting broad-scale uptake of modern screens; and (iv) outlining current activities and

Figure 1. Fish and debris blocking siphons (left) and in-line pipe filters (right) represent a problem for some irrigators with unscreened or ineffectively screened diversions. Images: Twitter user @irrigationbydave and Steve Detwyler.
future opportunities for screening in Australia.

Evidence of Fish Losses and Population Impacts

Historical accounts

The loss of native fish at water diversions in the MDB is not a recent problem. There are numerous accounts of losses, and calls for diversion screening, dating back to the beginning of last century. Ten newspaper articles spanning 1922–1947 are summarised in Appendix S1. They outline losses (sometimes in their thousands) of species such as Murray Cod (Maccullochella peeli), Golden Perch (Macquaria ambigua), River Blackfish (Gadopsis marmoratus), Macquarie Perch (Macquaria australasica) and Bony Herring (Nematalosa erebi) at gravity-fed diversions off the Murrumbidgee and Murray Rivers.

An indication of the scale of the losses is that the Fisheries department at the time considered using irrigation channels as native fish hatcheries and having staff employed to recover fish when channels dried (Murrumbidgee Irrigator 1946). Although these recommendations were never implemented, today government staff do on occasion rescue fish stranded in irrigation channels. For example, in June 2020 the Victorian Fisheries Authority rescued from the Lake Mulwala and the Shepparton-Waranga irrigation channels of the Murray River: 1207 Murray Cod, 143 Golden Perch, 199 River Blackfish (Gadopsis marmoratus) and one Silver Perch (Bidyanus bidyanus) (J. Douglas, pers. comm., 2020).

Contemporary research

Since the late 1990s, fisheries scientists have started quantifying fish losses at both gravity-fed diversions (Gilligan & Schiller 2003; Baumgartner et al. 2007; King & O’Connor 2007; Jones & Stuart 2008; O’Connor et al. 2008) and pumps (Baumgartner et al. 2009; Boys et al. 2013b; Brown et al. 2015; Norris 2015). A number of reviews have also been undertaken (Blackley 2003; Baumgartner 2005; Baumgartner & Boys 2012). Because the susceptibility of fish to entrainment is also related to their ecology and behaviour, our understanding of the impact has also improved as the body of ecological knowledge of Australian native fish has grown (Koehn et al. 2020).

Gravity-fed diversions. Large losses of fish occur at gravity-fed water diversions. Sampling at an environmental regulator channel (Barmah forest, Murray River) returned 15 800 small-bodied and 434 large-bodied native fish (including Golden Perch, Murray Cod, Silver Perch and Bony Herring) (Jones & Stuart 2008). In an investigation of the Murray Valley and Torrumburry Irrigation systems, more than 10 000 native fish comprising 10 different species were found in the channels, including six threatened species (O’Connor et al. 2008).

A count of native fish below a hydroelectric plant on the Mulwala Canal (off the Murray River) exceeded 950 000 individuals (Baumgartner et al. 2007). Many of the fish were small-bodied species such as Unspecked Hardhead (Craterocephalus stercusmuscarum fulvus), Australian Smelt (Retropinna semoni) and Carp Gudgeon (Hypseleotris spp.). Juveniles of larger-bodied species such as Murray Cod, Golden Perch and River Blackfish were also caught.

Active downstream migration of large adult fish mean they can follow the bulk flow of water into gravity-fed diversions (Lintermans & Phillips 2004; O’Connor et al. 2008). At Yarrawonga Weir on the Murray River, most of the low to medium flows are diverted into irrigation channels or a power station. Impingement on trash screens has included adult Golden Perch, Murray Cod up to 30 kg and freshwater turtles (Stuart et al. 2010).

Early life stages of fish appear even more vulnerable and many diversion channels are dominated by 0+ or 1+ age classes (King & O’Connor 2007; O’Connor et al. 2008). Australian native species can produce thousands of eggs per spawn (Harris & Rowland 1996; McDowall 1996; Koehn et al. 2020). Pelagically spawned, buoyant or semi-buoyant life stages (i.e. eggs and larvae) have little or no swimming capacity and drifting with the flow is an obligate part of their life history (Koehn et al. 2020). Therefore, significant numbers are swept along by diverted water. The distribution and timing of this larval movement are important. Higher densities of drifting larvae can be found along river edges and benthic zones (e.g. Tonkin et al. 2007) where channel (or pump) inlets are located, and the peak season for breeding and larval drift coincides with the peak spring and summer irrigation periods, or coincides with flow pulses when water users have access to additional or supplementary entitlements.

Figure 2. Most diversions in Australia are either unscreened or use coarse mesh or bars that are ineffective at reducing the velocity at the intake and excluding fish and small debris. Photographs: Craig Boys.
Of cod larvae was about half of that estimated during November, the peak time for downstream drift of this species (Baumgartner et al. 2007). This density of cod larvae was about half of that drifting down the river (Baumgartner et al. 2007).

**Pump diversions.** There are four published studies documenting fish losses at pump diversions. One sampled larval and larger fish at two diversions (maximum capacity 35 and 150 ML/day) on the Namoi River (Baumgartner et al. 2007; Baumgartner et al. 2009). Per day, 232 fish (70% native, 30% alien species and mostly small-bodied species) were diverted at a rate of one native fish per ML.

Another study sampled the entire volume of water diverted at an experimental pump (35 ML/day), also on the Namoi River (Boys et al. 2012; Boys et al. 2013b). On average, 3.5 native fish per ML were diverted. Larval fish were not targeted in the sampling and most fish caught were less than 40 mm in length. Catches were dominated by native Carp Gudgeon, Australian Smelt and Spangled Perch (*Leiopotherapon unicolor*)—corresponding to the species most abundant in the river near the pump.

One study examined a 300 mm diameter intake pipe at Oakey Creek in the Condamine catchment (Norris 2015). Over 9000 Australian Smelt were extracted in a single afternoon. This species comprised 75% of the fish extracted by the pump but only 0.3% of all fish sampled from the creek. The shoaling nature of Australian Smelt may have made large numbers susceptible to being entrained. Juvenile Freshwater Catfish (*Tandanus tandanus*) were also recorded. A total of 12 247 fish (all but eight being native) were extracted in 14 ML of diverted water, equating to a rate of 887 fish per ML.

The final study documented fish losses at a group of environmental pumps on the Murray River during an environmental watering event (92 000 ML) of Hattah Lakes in 2014 (Brown et al. 2015). Fish were netted as they discharged from the pumps and subsequently sampled exiting the system when the lakes were drawn down. The study provides evidence that native species (n = 626) comprised 91% of all fish sucked into the pumps. Relative abundance of native species in the Murray River was a reasonable predictor of relative abundance removed by the pumps. The native species impacted (in order of decreasing abundance) included Bony Herring, Australian Smelt (eggs and adults), Carp Gudgeon, Golden Perch (40–10 mm), Silver Perch, Un-speckled Hardyhead and Murray Cod. The vast majority of fish passing the pumps (75%) were injured by de-scaling, decapitation or exophthalmia (a type of eye injury), including Bony Herring (74%), Silver Perch (33%) and Golden Perch (8%).

The authors know of one unpublished record of fish losses at a pump diversion at Bourke on the Darling River. In 2003, during the millennium drought, NSW Fisheries researchers rescued over 300 adult Golden Perch and smaller numbers (less than 20) of Silver perch from Gidgee Lake, a large storage dam (C. Boys, pers. comm., 2021).

**Population impacts**

So far, details have been provided of localised losses at individual diversions. But what impact are these having on fish?
populations both at local and broader geographic scales? Firstly, it is important to highlight that once fish are entrained at a diversion, they are removed from breeding populations forever and the impact therefore accumulates over successive generations. Irrigation channels are typically unsuitable for fish due to their lack of permanent water, poor water quality, high bird predation rates and a lack of suitable habitat (Redding & Midlen 1991). So while large numbers of larvae may drift into irrigation systems, it is rarer to capture these fish surviving in storage dams beyond a year old (Baumgartner et al. 2007; O’Connor et al. 2008). If passing through pumps, many fish do not survive (Brown et al. 2015). Therefore, early suggestions from government fisheries agencies that irrigation channels would make good nurseries for fish (Narrandera Argus & Riverina Advertiser 1946) are not valid in most instances.

The scope of population impacts firstly relates to the ecology of Australian species, which makes them susceptible to entrainment in such large numbers, therefore reducing recruitment (progression into the adult population) (O’Connor et al. 2008; Koehn et al. 2020). However, this ecological susceptibility is compounded by the significant number of diversions and large volumes of flow diverted across all rivers. These cumulative losses across many diversions only exacerbate the other key threats being experienced by native fish – such as river regulation and changing flow regimes, barriers to fish passage, habitat destruction and invasive species (Koehn & Lintermans 2012). Compared to other impacts, the impact of diversions on fish extraction has been largely underestimated, and the relationship between the quantum of flow diverted from rivers, fish losses and the impact on fish populations is rarely articulated.

In some countries it has been reported that the number of fish lost at diversions is generally positively correlated to volume of water extracted (Moyle & Israel 2005). Therefore, knowing what proportion of river flow is being extracted and combining this with what information is available on fish losses at gravity-fed and pump diversions can allow predictions to be made about fish population impacts in Australia.

**Population impacts due to gravity-fed diversions.** In the MDB, four of the largest irrigation areas divert water using gravity-fed channels. The last twenty years of data reveal that in the Mid-Murray River, up to 60% of flow is diverted at Yarrawonga Weir, and a further 66% of the remaining flow at the next downstream weir at Torrumburry (2001–2021 diversion data, https://riverdata.mdba.gov.au/, accessed 9 March 2021). This is a potential cumulative total of up to 86%. At Goulburn Weir on the Goulburn River, up to 97% of flow is diverted (2001–2021 diversion data, https://data.water.vic.gov.au/, accessed 12 March 2021). Finally, at Berembed Weir on the Murrumbidgee River up to 76% of flow is diverted (2012–2020 diversion data, https://realtimedata.waternsw.com.au/, accessed 12 March 2021).

Large volumes of water diverted can lead to large losses of fish, and population impacts increase significantly once multiple diversions are considered. At the major Mid-Murray River diversions mentioned previously, using the data of Gilligan and Schiller (2003) we conservatively estimate that due to extraction there would be 580 000 to 1.2 million less fish surviving to 12-month old fingerling stage (depending on whether mean annual loss or maximum annual loss values are used). These figures account for baseline mortality that may occur naturally: that is, 10 cod larvae or 200 drifting perch eggs only produce one fingerling (C. Todd, pers. comm., 2019). For perspective, 1.2 million fingerlings is 1000 times the number of fish stocked into that reach over the past 5 years, and approximately 75% of average annual stocking efforts across NSW by government (2015–2020 NSW DPI stocking data).

**Population impacts due to pump diversions.** The MDB Plan (MDBA 2012) allows for the diversion, on average, of over 10 million megalitres per year for consumptive use (mainly irrigation). In high rainfall years, the proportion of river flows diverted may be minimal, however in low-flow and drought years, the proportions can be much larger. According to river flow analysis (Mallen-Cooper & Zampatti 2020), in 2018–2019, in the NSW portion of the northern MDB – where there are mainly pumped diversions – 768 000 megalitres was released from upstream dams for irrigation, and 163 000 megalitres released for the environment. During this same time, river flow ceased downstream of the main irrigation areas and environmental watering sites for 14 months (measured at Bourke on the Barwon-Darling River). While acknowledging there are evaporative and transmission losses, most flow delivered for irrigation purposes was diverted – as were any fish entrained in that water.

The scope for population losses from pump diversions can be estimated in NSW, where there are over 4500 licensed pumps with intakes ranging from 200 to 290 mm diameter and extraction rates estimated at 10–220 ML/day (DOI Water unpublished 2015 data; Fig. 4). The majority of these are in the northern MDB. Using conservative (3.5 fish per ML, Boys et al. 2012) and a high (887 fish per ML, Norris 2015) fish extraction rates, together with the previous example of 768 000 megalitres used by pumped irrigation in the NSW portion of the northern MDB in 2018–2019 (less 25% of the volume due to riverine transmission losses), the loss of native fish in the NSW northern MDB alone could be between 2 and 510 million a year. Although data obtained from pump studies to date are dominated by ubiquitous small-bodied, generalist fish species, less abundant and threatened species like Murray Cod, Golden Perch, Silver Perch and Freshwater Catfish are also included in these losses.

**The Solution: Fish- and Farm-Friendly Screens**

A screen is available for any diversion

Whilst not all diversions may need to be screened, every diversion is capable of being screened – at any size. Different types of screens can be used in different...
contexts – whether they be pump or gravity-fed channels, in shallow or deep water, permanently submerged or requiring retrieval (Fig. 5). There are self-powered rotating cylinder screens for pumps diverting as low as 3 ML/day and up to 50 ML/day. At the other end of the scale are powered cone screens (capable of up to 200 ML/day) or ‘t-configured’ cylinder screens (capable of over 300 ML/day). In order to maintain a fish-friendly approach velocity, the bigger the diversion, the bigger the screen needs to be, or the more screens that need to be connected in series. For example, the 715 ML/day screen on the Trangie–Nevertire Irrigation Scheme pumps (Macquarie River NSW, Fig. 5e) consists of four 3-mm cones. New Zealand’s Rangitata River Diversion Race (Fig. 5f) screens consist of seven individually retractable cylinder screens, collectively capable of filtering flows in excess of 2800 ML/day through a 2 mm mesh. A 335m long flat plate screen on the Sacramento River (USA) is used to exclude fish from the 7339 ML/day Glenn Colusa Irrigation Canal.

**Figure 4.** There are over 4500 licensed pumps with an intake pipe of 200 mm or greater across NSW rivers (2015 Data NSW DOI Water). Light shading indicates the vast majority of these are in the Murray–Darling Basin.

**Screens tailored for Australian conditions**

Not all screens are created equal – just because a screen can exclude debris does not mean it will protect fish. Stakeholders require scientific and practical guidance on appropriate technologies, their design, construction, installation and operation. Today’s modern screens have evolved over decades of performance testing in laboratories (e.g. Zydlewski & Johnson 2002; Swanson et al. 2004; Poletto et al. 2015) and on actual diversions (e.g. McMichael & Chamness 2001; McMichael et al. 2004; Walters et al. 2012). However, this has mostly been in the United States and for the protection of salmon and trout. Australian rivers have unique hydrology and geomorphology, with native fish having specific ecological and biological traits. It is therefore important to ensure that screen technologies that work successfully overseas are tested and adapted to suit Australian conditions, employing design and hydraulic characteristics to meet the swimming capabilities of resident species.

 Fortunately, this process of testing and adaptation is already well-advanced in Australia so that screens can be installed with a high degree of confidence. Laboratory and field studies focusing on young-of-year and older fish have now been completed (Boys et al. 2012; Boys et al. 2013a; Boys et al. 2013b; Stocks et al. 2018) and further studies on fish eggs and larval fish are nearing completion. They show that internationally accepted approach velocities of 0.1 m/s will successfully reduce losses of Australian native species by over 90%. Studies are now underway to validate these results in the field and the collective international and domestic research is being used to produce the first national guidelines for diversion screen design in Australia (due for publication in 2021).

**Benefits for fish and farms**

Broad uptake of modern screens could deliver significant benefits for fish and farms, complementing river restoration programmes and stimulating regional economies. In the MDB, AUD$13 billion has been dedicated to conserving and recovering waterways through the delivery of environmental water and improving irrigation practices. An increasing element of these efforts needs to be the use of complementary fish recovery measures, that are non-flow based (Baumgartner et al. 2020). Installation of modern screens has been identified as one such measure and a priority area for investment under the Native Fish Recovery Strategy, with potential on-farm benefits for water users through infrastructure and operational savings (Boys & Rayner 2020; MDBA 2020). Screening and better debris control support the adoption of pressurised irrigation methods (sprinkler and drip), which are generally less labour-intensive and have significantly higher water-use efficiency (Koech & Langat 2018).

The benefits of modern screens extend beyond fish and farms (Perkins 2015). Screen construction and installation stimulates regional economies through manufacturing and logistics involving the design, fabrication, and water engineering sectors (Baumgartner & Boys 2012; Boys & Rayner 2020). The manufacturing
potential in NSW alone is huge, based on 4500+ licensed pumps and many gravity-fed diversions. The indirect social, economic and cultural values of enhanced native fish populations could also be substantial (Ernst & Young 2011, Barwick et al. 2014, NSW DPI 2018).

**Screen Modernisation and Social learning: Fish Screens Australia**

The United States has been screening diversions for over a century and Australia can learn from the strategic and coordinated approach that has particularly been applied in recent decades (Baumgartner & Boys 2012). There, planning of projects is a collaborative process, where natural resource agencies work with fishing bodies, private farmers, larger irrigation schemes, and whole irrigation districts (Perkins 2015). The focus is on optimising irrigation systems across the whole farm (intake to where water is delivered) to reduce costs, improve water efficiency and protect the environment.

In the United States they have a saying: ‘No one sells a screen like a farmer with a screen’ (L. Perkins pers. comm., 2015). This statement has its roots in diffusion of innovation theory, which explains how over time a new idea, practice or product gains momentum and spreads through society (Rogers 1962). In simple terms, the best way to gain broad acceptance is by first demonstrating the benefits with early adopters – often industry leaders respected among their peers. Once tangible benefits can be reliably demonstrated and communicated, an innovation is likely to be accepted by the broader community (Moore 1991).

The Fish Screen Australia (FSA) research and extension programme was created based on this theory. Some of its key features are as follows:

- The Australian Fish Screening Advisory Panel – a multi-jurisdictional panel of water users, fishers, scientists, managers and engineers enabling knowledge exchange and collaboration, and facilitating a consistent approach to the co-design and implementation of screening projects across the country.
- Showcase projects demonstrating modern screens in use at a range of diversion types and water operations (Table 1).
- Research aimed at: documenting fish losses; improving screen design; evaluating screening projects; and, understanding the needs of water users.
- Production of Australia’s first best-practice guidelines for fish screen design and installation.
- A stakeholder targeted and managed information website with the goal of

![Figure 5](image-url)

*Figure 5.* Both gravity-fed and pump diversions across a wide range of flows can be screened. Cone screens can be used in shallow water on both large pumps (e) and gravity-fed channels (a). Vertical (b) and horizontal (d) screens can be used for gravity-fed diversions. Cylinder screens are suitable for both small (c) and large (f - computer rendering) diversions. Photographs: Craig Boys (b–e) and AWMA (a, f).*
| Project                          | Installed | Location                      | Diversion and project description | Screen type                                                                 |
|---------------------------------|-----------|-------------------------------|-----------------------------------|-----------------------------------------------------------------------------|
| Dubbo Turf Farm                 | 2021      | Dubbo, Macquarie River NSW    | 5 mL/day centrifugal pump          | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) mounted on a pontoon that can be floated for screen inspection |
| Forbes Farm                     | 2021      | Forbes, Lachlan River NSW     | 5 mL/day centrifugal pump          | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) mounted on a pontoon that can be floated for screen inspection |
| Narrandera Fisheries Centre     | 2021      | Narrandera, Murrumbidgee River NSW | 4 mL/day centrifugal pump supplying the NSW Department of Primary Industries Narrandera native fish hatchery ponds | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) mounted on a pontoon that can be floated for screen inspection |
| Taronga Zoo                     | 2021      | Dubbo, Macquarie River NSW    | Two 5 mL/day axial flow pumps for main water source of the Zoo | Two 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.), retractable. |
| Central West Farming Systems    | 2020      | NSW Department of Primary industries Agricultural Research & Advisory Station, Condobolin, Lachlan River NSW | 10 mL/day centrifugal pump irrigating 120 ha of winter cereal for CWFS, an independent, not-for-profit, farmer driven organisation with the goal of advancing research in agriculture | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) mounted on a pontoon that can be floated for screen inspection |
| Jim-Dara Pastoral Co            | 2020      | Farley Reserve, Cowra, Lachlan River NSW | Two axial pumps deliver up to 8 mL/day through pressurised pipeline to hand-placed pipe and sprinkler. Modern screens replaced an ineffective polypipe cylinder with 12mm perforations | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) |
| Koondrook Farms                 | 2020      | Koondrook, Gunbower Creek Vic | Two 10 mL/day centrifugal pumps utilised on two farms for pivot irrigation | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) mounted on a pontoon that can be floated for screen inspection |
| Murrabit Farms                  | 2020      | Murrabit, Murray River Vic.   | Six 10 mL/day and one 25 mL/day centrifugal pump utilised on various farm sites for pivot & lateral irrigation | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) mounted on a pontoon that can be floated for screen inspection |
| Oakben Agricultural Company     | 2020      | Dubbo, Macquarie River NSW    | 10 mL/day axial pump irrigating a mixed crop of cotton, corn and mung beans with lateral move and centre pivot overhead sprinklers | 2-mm wedge wire (self-powered) rotating, brushed cylinder screen (AWMA Water Control Solutions, Cohuna Vic.) |
| Porker Citrus                   | 2020      | Eillerslie (near Wentworth), Darling River NSW | 6 mL/day centrifugal pump with drip irrigation of grape and citrus | 62 micron rotating woven mesh Riverscreen™. The screen floats on the surface, only being partly submerged, and is cleaned with external spray jets (Eagle I Machinery, Finley NSW) Four 3-mm wedge wire (hydraulically powered) brushed cone screens (AWMA Water Control Solutions, Cohuna Vic.) |
| Trangie-Nevertire Irrigation Scheme | 2020  | Trangie, Macquarie River NSW  | Up to 715 mL/day through 4 individual axial pumps supplying a member-owned organisation managing 100 000 hectares of mixed farming enterprises and almost 21 450 hectares of irrigation. | |
Dewfish Reach  2019  Oakey Creek, tributary of the Condamine River Qld  30 mL/day pump  Woven mesh fixed-cylinder Kleenscreen™ (aperture not confirmed) with rotating internal water spray cleaning (Dama Manufacturing Ltd, Whangarei NZ)  Number 3 Offtake Gunbower Creek (Goulburn-Murray Water)  2018  Cohuna, Gunbower Creek tributary of the Murray River Vic.  600 mL/day gravity-fed diversion off the Cohuna weir  Four 3-mm wedge wire (hydraulically powered) brushed cone screens (AWMA Water Control Solutions, Cohuna Vic.)  Orange Pipeline (Orange City Council)  2015  Cobbs Hut Hole (nearest major town Orange), Macquarie River NSW  12 mL/day pump diversion feeding a 39 km municipal pipeline to secure water supply for the town of Orange  2-mm wedge wire fixed cylinder screen Johnson™ with airburst cleaning (Aqseptence Group, Geebung Qld)  

Table 1. (Continued)

The Challenge Ahead

To realise the benefits of modern screening in Australia, there needs to be greater acceptance of the evidence of fish losses and their impacts, along with a better understanding of the technologies currently available to solve the problem. It is our hope that this paper, along with programmes like FSA, make a constructive contribution in this respect. Once the impact and solutions are acknowledged, more focus can be directed to overcoming the barriers to adopting a new best-practice for water extraction in Australia. This includes resolving questions around where investment should be prioritised, how will it be funded and how screening can be better integrated within water and environmental policy. Answering these will be challenging, however addressing them will be critical to progressing screening at a scale required to benefit fish populations.

Moving forward, it is likely that screening projects will need to be funded through a mix of private and public investment, depending on the value proposition. In many instances, farmers will justifiably cover the full cost of screening because the return on investment from reduced operational and maintenance costs is economically attractive. Others may choose to invest in screening because doing so strengthens their environmental stewardship and social licence to operate.

Screens are a major capital outlay and like any piece of infrastructure do require ongoing investment in maintenance. Some water users may be initially incapable or unwilling to invest their own money, regardless of any environmental benefits that might occur. In cases where the economic return to the user is marginal or where there is a strong environmental imperative to screen, incentivising uptake with public funds may be appropriate. This could come in the form of subsidies or taxation benefits (Baumgartner & Boys 2012).

Australia has experience investing public funds in the modernisation of private water infrastructure. Under the 2008 Water for Future Plan, AUD$5.8 billion in subsidies were allocated for water infrastructure modernisation, with the intention of increasing irrigation efficiency (Grafton 2019). Although screen modernisation was not included in that program, this is now being addressed and screening has been included as a measure in the Northern Basin Toolkit, with a focus on promoting fish movement and habitat rehabilitation to deliver on Basin Plan outcomes.

Knowing where and how to start investing in modernisation is daunting, given the sheer number of diversions across Australia. Screening every diversion will not be feasible, even if the willingness was there. Conservation funds are limited and have competing demands. However, we should not invest in screening under the assumption that all diversions are equally worthy of modernisation. Whilst all diversions can remove fish, they can vary greatly in their impacts. Prioritisation will be required and needs to consider both how water is diverted and river ecology.

To strategically invest to deliver the best population outcomes, a more thorough understanding of the impact across different diversion types, rivers and whole catchments is required. This has been done poorly overseas (Moyle & Israel 2005) and has still to be attempted on a large scale in Australia. It may be that below a certain size, diversions have minimal impact and are less worthy of investment. Focus may therefore need to be on medium to large diversions that divert significant amounts of water and fish. However, even when the largest diversions are screened, there will be thousands more still impacting fish. Therefore, size cannot be the only consideration. It may also be that due to their location or operating behaviour, even smaller diversions in some areas may have a disproportionate impact on rare or endangered species.

Screening works could also be better embedded in environmental and water planning processes. They could be prioritised in areas where other native fish recovery actions are planned, such as...
fishways, re-snagging, environmental flow delivery or cold water pollution mitigation. All these actions aim to improve fish spawning and recruitment, and their success would be undermined if fish losses at diversions are not addressed at the same time. Where pumps or gravity-fed diversions are installed to facilitate the environmental watering of wetlands, this should be done in a way that doesn’t injure or kill fish (Jones & Stuart 2008; Brown et al. 2015). There is also significant scope to examine the role of screening in relation to water sharing plans (e.g. how supplementary access licencing and floodplain harvesting may impact on fish losses) and actions to protect and conserve threatened species (e.g. recovery plans).

**Conclusion**

Recent catastrophic fish deaths across the MDB (Vertessy et al. 2019) have heighted public awareness of the declining health of Australia’s rivers and again stimulated public interest in protecting and restoring native fish populations. Modern screening undoubtedly has a role to play in this recovery alongside other complementary measures. However, success depends on genuine partnerships. Criticism of water users is counterproductive. Instead, continued collaboration is required between scientists, water users, anglers, natural resource managers, engineers and manufacturers. This is the goal of FSA, and together our focus needs to shift from the problem to its solution and tackling the remaining challenges that lie ahead. By returning benefits for fish, fishers, farmers and manufacturers, screen modernisation can provide both direct and indirect returns on investment for regional towns as they recover from bushfires, drought, flooding and the global COVID-19 pandemic. In this respect, modern screens deserve real consideration as a highly effective measure to support both farming and fish recovery.

**Acknowledgements**

The authors undertook this work as part of the ‘Fish Screen Australia’ project, funded by the New South Wales Recreational Fishing Trust and the Ian Potter Foundation. Deanna Duffy (CSU) and Karen Danaher (NSW DPI) prepared the maps. Peer review by Anthony Townsend and Katherine Cheshire (NSW DPI), Les Perkins and particularly Martin Mallen-Cooper greatly improved the manuscript. We would like to acknowledge the effort of those forward-thinking farmers, staff of NSW Government (particularly Sam Davis, Casey Proctor, Dominic Nowlan and Kaye Gottschutke), OzFish Unlimited and members of the Australian Fish Screening Advisory Panel who are leading transformational change and a new best-practice for the way water is diverted in Australia.

**Conflict of Interest**

The authors declare no conflict of interest.

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**Supporting Information**

Additional supporting information may be found online in the Supporting Information section at the end of the article.