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Reducing the perversion of diversion: Applying world-standard fish screening practices to the Murray–Darling Basin

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Summary The impact of water diversion on fish populations is a global issue. Many countries have invested substantial funding into research and implementation strategies to ensure fish are protected at diversions that take water out of rivers for agriculture and other human uses. The most common management action is the installation of fish screens, and a wide range of designs are presently available that suit a large range of diversions. The Murray–Darling Basin is the largest catchment in Australia and has been substantially developed over the past 100 years to store and divert water for that protect fish from escaping into the irrigation systems. Recent studies have determined that water diversions have substantial impacts on native fish populations, but there are presently no coordinated efforts for mitigation strategies. The purpose of this review is to highlight aspects of successful screening programmes worldwide and identify those that could be directly applied to the Murray–Darling Basin. The development of similar programmes in the United States, New Zealand and the United Kingdom has identified that sufficient information and technology exists to inform the development of fish screening programmes. There is no need to commence implementation from first principles, and substantial progress can be achieved by applying successful aspects of other programmes. By identifying existing designs, defining ecological targets, developing generalised guidelines appropriate for local conditions and engaging the community, a co-ordinated and successful fish screening programme could be directly applied to the Murray–Darling Basin. This would have substantial benefits for the long-term sustainability of native fish without compromising water supply requirements.

Key words: *diversion, fish screen, irrigation, legislation, mitigation, Murray–Darling Basin.*

Introduction

Increasing demand for water worldwide is placing enormous pressure on the biodiversity of freshwater ecosystems (Dudgeon *et al.* 2006). Worldwide, the development of irrigation works has increased exponentially over the past 50 years (Fernando & Halwart 2000). This has been crucial to enhance global food production, but has had a substantial impact on river flows and ecological processes (Davies *et al.* 2000). The regulation of river flows through water impoundment, diversion and abstraction is widespread, but tends to be most severe in regions with highly variable flow regimes (Vörösmarty *et al.* 2000; Dudgeon *et al.* 2006). It is estimated that every 1000 ha of irrigated land requires the creation of 2.5 km of large irrigation channels and 10 km of smaller tributary channels (Redding 1991). Increased future demand for irrigated produce will facilitate a need for irrigation infrastructure to remove more water from rivers. Such development will necessitate appropriate management strategies to reduce negative impacts on aquatic biota, particularly fish.

Water diversion can impact fish by altering habitat and disrupting flow-dependent life-history strategies (e.g. spawning and recruitment) (Walker 1985; Humphries *et al.* 2002). The physical removal of fish from rivers via direct entrainment at water diversions can also be significant and has been implicated in species declines throughout the world (Moyle & Williams 1990; Musick *et al.* 2000). Mechanical injury and substantial mortality can occur during entrainment, but fish are also permanently removed from the main channel (Prince 1923), which can lead to recruitment failure (McMichael *et al.* 2004). Fish declines have therefore been substantial where water development is intensive, and in some cases, the cost of mitigating impacts can be prohibitive (Williams 2008). In many countries, the true impact of diversion infrastructure on fish remains unquantified especially where mitigation techniques and programmes are yet to be established.

Where impacts on fish have been quantified and understood, the most commonly applied mitigation measure to prevent fish entrainment is the installation of physical screens. Screens aim to create a physical barrier that direct fish away from the diversion point and back to the river (Neitzel *et al.* 1990). Screens come in a variety of designs, but the appropriateness of any specific design depends largely on the species to be protected, volume of flow, type of diversion system and ongoing maintenance requirements. The swimming ability of target species is the primary factor ultimately determining the design and size of a screen (Anon 1997). Fish screening laws have been developed in many countries to control the impact of irrigation diversions on riverine fish communities (Brannon 1929; Kepshire 2000; Charteris 2006; Carlson & Rahel 2007). Critical to this process has been the development of several strategically coordinated and prioritised screening programmes that were initially informed by an evidence-based research approach (e.g. McMichael *et al.* 2004; Peake 2004; Cech & Mussen 2006; White *et al.* 2007). A combination of focussed research, adaptive management and incentive programmes has facilitated large-scale recovery programmes targeted primarily towards freshwater fish (Kepshire 2000). Despite the success of programmes globally, there has been no similar programme developed for Australian systems. Australian native freshwater fish remain in decline, and little research is available on the impact and mitigation techniques at water diversions. Much information is available internationally, but is contained within grey literature reports and can be difficult to access. This review sought to examine both published and grey literature information to identify existing research and management outcomes that have led to the development of successful screening programmes globally. The key components responsible for success were identified and developed into a conceptual framework for development of a screening programme to help mitigate impacts diversion structures within the Murray–Darling Basin.

Flows and Water Diversion in the Murray–Darling Basin

The Murray–Darling Basin is Australia's largest catchment covering over one million square kilometres and draining water from five separate states and territories. Its main river system is the Murray River (2560 km), which rises in the alpine regions of southern New South Wales (NSW) and meets the sea at the Coorong estuary in South Australia. Much of the Murray-Darling Basin is located in semi-arid-to-arid climatic zones with low mean annual rainfall (430 mm) and high evaporation (King 2002). Ninety-eight per cent of the catchment contributes little or no run-off, and subsequently, the system has a relatively small annual discharge (12 200 GL) (Crabb 1997). Despite such relatively low discharge, the Murray–Darling Basin supports at least 40% of Australia's agricultural production (MDBC 2003) and a population of over two million people (Jacobs 1990).

Irrigation is the largest user of water in the Murray–Darling Basin (Jacobs 1990). Agricultural practices in the Basin are extensive, but diverse, and a variety of crops are annually cultivated, including wheat, barley, corn, rice, cotton, grapes, citrus and vegetables. To adequately service these crops, an average (between 1988 and 1994) of 10 232 GL of water per year (Jacobs 1990) is diverted from rivers within the Basin to irrigate a total of 670 000 ha of land (Young 1999). In contrast, extractions for town supply and domestic use are substantially lower at 452 GL per year (Jacobs 1990). In some cases, the amount of water extracted or diverted at weirs represents a large proportion of the total flow within individual rivers. For example, during times of peak irrigation demand, volumes of water diverted to the Murrumbidgee Irrigation Area are up to 280% greater than flows downstream of the weir (Baumgartner *et al.* 2007).

Fish Declines and Losses at Diversions in the Murray–Darling Basin

The ecosystem health of the Murray–Darling Basin has declined over the last 100 years largely owing to water extraction, land clearing, alteration of natural flow regimes, riparian degradation and reduced connectivity (Reid & Harris 1997). Over 95% of the Murray River is degraded in some capacity, and 40% of the river length contains biota that has declined in both range and abundance (Parsons *et al.* 2004). Whilst the degradation of the Murray-Darling Basin has had detrimental effects on virtually all resident biota (Gippel & Collier 1998), impacts on the abundance and diversity of native fish have been particularly profound (Cadwallader & Lawrence 1990; Gehrke 1997). Historical catch data on golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*) and Murray cod (*Maccullochella peelii*) recorded from a fish trap at Euston Weir (Murray River) have demonstrated that over 50 years, numbers have declined by 51%, 94% and 96% (respectively) (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 eventual closure (Reid & Harris 1997). Of the 46 native fish species known to reside in the Basin, 26 are now listed as threatened under either state or commonwealth legislation (Lintermans 2009), and the entire lower Murray–Darling fish community has been listed as threatened. Native fish numbers within the Murray–Darling Basin are estimated at 10% of pre-European levels (MDBC 2003).

Multiple key threatening processes have contributed to fish declines (Barrett 2004), but the issue of fish losses at water diversion has remained unquantified until recently (Lintermans & Phillips 2004; King & O'Connor 2007). The few studies that have been conducted suggest that the problem may be substantial (King & O'Connor 2007; Baumgartner *et al.* 2009) and that a diverse range of species and significant numbers of fish can be entrained by both pumps and gravity-fed diversion canals. Larger-bodied fish are known to enter irrigation canals or be entrained by pumps, but early life stages (eggs, larvae and 0+ fish) appear to be the most affected owing to a drifting dispersal strategy and poor swimming ability (Gilligan & Schiller 2003; King & O'Connor 2007). Early life stages of Murray cod, golden perch, silver perch and trout cod (*Maccullochella macquariensis*) have drifting phases that correspond to peak periods of irrigation abstraction (November and December) (Gilligan & Schiller 2003; Humphries & King 2004). Larval drift studies have suggested that millions of eggs and larvae are vulnerable to abstraction from the main river and many species are susceptible to desiccation when irrigation canals are dried during the Austral Winter (Gilligan & Schiller 2003; King & O'Connor 2007).

Studies of fish entrainment at diversions in other countries similarly indicate that millions of eggs and larvae are removed via irrigation diversions (Allen 1975; Spaar 1994). At irrigation diversions at Lake Havasu, Arizona, it was determined that approximately 3 million larvae were extracted each day (Mueller 1996). Similarly, between 6000 and 15 000 larval fish were estimated to be entering the Marchfeldkanal system from the Danube River (Austria) on a daily basis (Unfer & Schmutz 1998). These studies further concluded that the probability of entrainment was proportional to the size of main river populations and the amount of water being diverted. The volume of water diverted during peak irrigation times can far exceed downstream flow at some sites within the Murray-Darling Basin (Thoms *et al.* 2004; Baumgartner *et al.* 2007; King & O'Connor 2007), greatly increasing the potential for fish loss. McMichael *et al.* (2004) contend that the extraction of even a small percentage of egg and larval production may represent a substantial loss of potential recruits from rivers. In the Murray-Darling Basin, many native fish species have been observed to regularly spawn, but not subsequently recruit, which has major implications for the sustainability of fish populations (Humphries *et al.* 2002).

These studies raise significant concern over the impact of diversions on fish populations in the Murray-Darling Basin. King and O'Connor (2007) have suggested that effective management solutions cannot be progressed until the true spatial extent of the problem is understood. Quantifying the extent and variability of the problem may be useful from a resource allocation perspective, but will only highlight spatial and temporal variabilities in impacts (Moyle & Israel 2005) whilst not eliminating the need for a mitigation programme. Most fish screening programmes in the United States apply a precautionary approach to fisheries management (Dayton 1989), where diversions are assumed to harm fish unless proven otherwise (Moyle & Israel 2005). Such an approach recognises that even small diversions have the capacity to impact fish populations and policies requiring that most diversions to be screened are strictly enforced in ecologically sensitive areas (McMichael *et al.* 2004).

A Co-ordinating Committee is Essential

Establishment of a co-ordinating committee is frequently seen as the critical first step in any screen design programme (Anon 2006) because it provides an important link between science and stakeholders. Committees provide overall direction, establish priorities, identify funding opportunities and standardise biological criteria for the construction of screens. Regular meetings involve researchers, irrigators and stakeholders responsible for managing fish populations (e.g. natural resource managers, anglers and other members of the public). The committees follow adaptive management principles and regularly update screen construction criteria based on newly available science, which is disseminated by researchers actively working in the field. The main benefit of a committee approach is the development, and acceptance, of a standard set of criteria that is understood and applied, which in turn leads to clear and consistent advice that can guide large-scale construction programmes.

When well-organised and resourced, committee advice can assist with the development of prefabricated equipment that can be supplied on a commercial scale (Anon 1997; Nordlund & Bates 2000). Various committees have similar functions in other countries, such as the fish screen working party in New Zealand (Jamieson *et al.* 2005), Hydropower Working Group in United Kingdom (Turnpenny *et al.* 1998), Fish Passage Technical Working group (Canada) and the working party on fish passage best practices (Europe). The Fish Passage Task Force (Barrett & Mallen-Cooper 2006) is an analogous group that already exists in the Murray-Darling Basin and has successfully advised on upstream fish migration issues, but is currently not mandated to consider fish loss at water diversions.

An Evidence-based Approach to Develop Screening Criteria

The establishment of clear objectives and requirements is required to guide the development and implementation of a screening programme. Fish screens need to be designed for local conditions, and early stages of programme development often focus on vulnerable species and life-history stages (Anon 2006). Targeted experimentation to determine screen design parameters for target species then follows. Screen design criteria need to take into account factors such as stream flow, diversion discharge and operating mode, as all relate to the optimisation of velocities close to the screen without compromising the delivery of water. Most guidelines usually stipulate critical screen design thresholds that should not be exceeded to protect target species of interest.

The ability for a fish to escape entrainment or impingement typically relates to the magnitude of velocities generated perpendicular to the screen (approach velocity) relative to that along the screen face (sweeping velocity) (Swanson *et al.* 2004). Reducing approach velocities relative to sweeping velocities minimises impingement risk. To achieve this, a screen may be angled, or alternatively spin, to increase flow across the screen. Research outcomes and site-specific construction needs are typically used to develop guideline documents that inform constructing authorities and stakeholders interested in advancing screen installation (Anon 1997; Nordlund & Bates 2000). This is an accepted framework in many countries with active fish screening programmes, but has yet to be developed for Australian rivers.

Laboratory studies of fish swimming capabilities, injury and mortality rates at simulated screens are normally used to inform guideline preparation. The ability to control hydraulic variables in a replicated and experimentally robust way allows specific aspects of screen design to be refined for a variety of flow conditions in a rapid and cost-effective manner (Zydlewski & Johnson 2002; Peake 2004; Swanson *et al.* 2005; White *et al.* 2007). Generic design criteria developed from these studies can then be implemented and field validated (McMichael *et al.* 2004). Field validation is important because screen performance and fish behaviour can differ between laboratory and riverine settings. For instance, screen design parameters determined to be acceptable for bull trout (*Salvelinus confluentus*) in the laboratory have resulted in impingement mortality when constructed in the field (Zydlewski & Johnson 2002).

The main challenge facing screening programmes in the Murray–Darling Basin will be a requirement to accommodate a diverse range of migratory species with very different swimming abilities (Mallen-Cooper 1999). Native fish in the Murray–Darling Basin are entrained at both large and small life-history stages (Baumgartner *et al.* 2009). Biologists and engineers are therefore presented with a considerable challenge to determine solutions that protect a diverse range of species and sizes of fish, whilst ensuring the needs of irrigators and other end users are not compromised. Many screening programmes elsewhere in the world are based around the primary objective of protecting endangered migratory salmonids during seaward migration phases (McMichael *et al.* 2004; Moyle & Israel 2005). Historically, other species impacted by diversions have rarely been considered when developing screen design parameters (Swanson *et al.* 2005). More recently, criteria for nonsalmonid species have been considered in an effort to afford protection to a greater proportion of fish assemblages, particularly threatened species. For example, additional criteria are considered at sites where known populations of delta smelt exist (*Hypomesus transpacificus*) (NMFS 1997). Similarly, New Zealand guidelines aim to protect several species of eel (*Anguilla* spp) and endangered galaxiids (*Galaxias* spp) (Charteris 2006).

Applying Existing Technologies in the Appropriate Context

A major consideration is which design is the most applicable to any given situation, but this is generally dictated by screening programme objectives. Fish protection is usually the sole motivation for any screening programme, so a useful starting point is to identify the smallest fish requiring exclusion because this will help define objectives (Anon 2006). Site-specific considerations are then taken into account. Generally, there are two main types of diversions in the Murray–Darling Basin: pumping intakes as typified in the northern Basin, and gravity-fed canals more common in the southern Basin (Baumgartner *et al.* 2007). There are, however, a huge range of site-specific differences in diversion design as well as discharge and intake positioning that will necessitate a diverse range of engineering solutions (Fig. 1). A wide variety of screen types are currently being applied in Europe (Turnpenny *et al.* 1998) and the USA (NMFS 1997) and could be readily adapted for application in the Murray–Darling Basin. Irrigation screening designs that are now routinely applied in New Zealand, for instance, are localised adaptations of designs that were developed elsewhere (Jamieson *et al.* 2005).

Once ecological targets and design guidelines are defined for the Murray–Darling Basin, the development of standard prefabricated designs could help to advance technology in a cost-effective manner on a large scale (Table 1). Most commercially available screens can be constructed of materials durable in aquatic environments, are self-cleaning, can operate using paddle or solar power and have flexible operating requirements. These features will be critical for application at diversions in remote areas of the Murray–Darling Basin. The technologies have also been developed, tested and refined over many years, so most advantages and

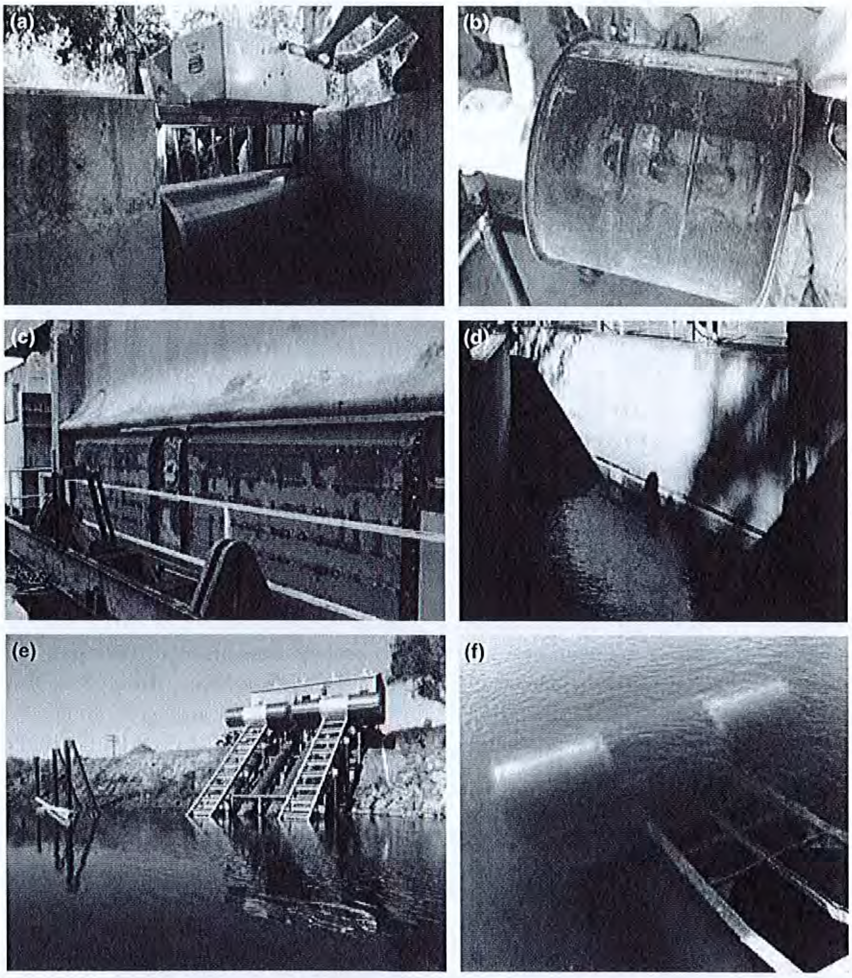

Figure 1. Various screen designs for potential application in the Murray–Darling Basin. (a) rotary drum screen (b) rotating pump screen with rotating head and internal jet (c) travelling belt screen, (d) vertical panel screen (submerged) with travelling brush and (e, f) brushed cylinder pump screen (e, f reproduced with permission of Intake Screens, Inc.).

Table 1. Fish Diversion screens with high potential for direct application in the Murray–Darling Basin (MDB)

Screen type	Features and suitability within the MDB	Summary of Murray–Darling Basin suitability				
		Small pump site (<100 ML per day)	Large pump site (>100 ML per day)	Small gradient-fed canal (<1000 ML per day)	Large gradient-fed canal (1000–10 000 ML per day)	Instream weirs dams
Rotary drum	Screens fitted to rotating drum. A slow rotation of the mesh allows debris to be effectively removed, thus preventing fouling. Suitable for low-gradient, smaller diversion canals in the southern MDB. Simple engineering keeps costs down. Can be powered by solar or paddle wheel for nonpowered sites. Can be made to suit canals with variable discharge by operating multiple bays or screens side-by-side (more screens are brought online as flow rate increases and shut-off as flow decreases)	No	No	Yes	Yes	Only when water is discharged over a fixed crest
Belt	Has a mesh panel, which vertically rotates in a manner analogous to a conveyor belt. This design requires low velocities at the screen to prevent fish impingement. It is self-cleaning, and debris simply collects and rotates with the screen. Requires power and more expensive than other types. Probably limited application at most diversions in the MDB, other than large dams in junction with downstream fish bypasses	No	No	No	Potentially, but not first choice	Yes
Vertical Panel	Suitable for larger gradient-fed diversion channels such as found in the lower MDB. Capable of accommodating greater fluctuations in river flow than rotating drum as submergence depth less critical. Needs to have an electric-driven brushing mechanism, typically in tandem with setting at appropriate angle to facilitate sweeping velocities across the screen face. *There is an example of one doing 300 ml per day in Oregon, but there is no reason why they could not be built to accommodate diversions such as Yarrawonga (3400 ml per day) or Mulwala (8000 ml per day)	Potentially, but not first choice	Potentially, but not first choice	Yes	Yes	Yes
Pump screens: Rotating pump or brushed cylinder	Rotating pump screens for small diversions (up to 30 ml per day when two run in tandem) can be purchased directly off the internet. They are self-cleaning by way of internal jet that sprays inside of rotating mesh screen (no power required). This action may make it suitable for reducing the entrainment and impingement of larval and eggs stages (although this needs to be verified). For larger pump sites, rotating wedge wire cylinders (powered) with internal and external brushes can be custom built for any discharge pump	Yes: rotating pump (<30 ml per day), brushed cylinders (>30 ml per day)	Yes (brushed cylinders)	No	No	No

Table 1. (Continued)

Screen type	Features and suitability within the MDB	Summary of Murray–Darling Basin suitability				
		Small pump site (<100 ML per day)	Large pump site (>100 ML per day)	Small gradient-fed canal (<1000 ML per day)	Large gradient-fed canal (1000–10 000 ML per day)	Instream weirs dams
Horizontal screen	Could be suitable for low-gradient diversion canals and has been demonstrated to be suitable for screening intakes to hydro electricity units placed on weirs. Farmers Conservation Alliance (FCA) has a patent on a unique design (Farmers Screen), which has low approach velocities and is self-cleaning whilst allowing 90% dewatering (10% for fish passage). Design specifications available from FCA on request	No	No	Yes	No	Yes

disadvantages are already understood. Construction, installation and maintenance costs are also well known and publicly available. Government bodies funding programmes and irrigators therefore have sufficient evidence upon which to make informed cost–benefit decisions. In some instances, fabrication workshops have been established to mass-produce screens on a commercial scale (Kepshire 2000), and screens could be directly purchased and imported. However, there are also likely to be many instances where retrofitting commercially produced technology will be difficult, and site-specific solutions will need to be developed.

Legislation, Regulation and Incentives

Elsewhere in the world, legislative obligations associated with endangered species have typically been the driver for fish screen development (Moyle & Israel 2005). Presently, irrigation screening legislation exists in North America (NMFS 1997; CDFG 2000), New Zealand (Jamieson *et al.* 2005), United Kingdom, Ireland, Switzerland, Netherlands, Denmark (Turnpenny *et al.* 1998) and France (Larinier 2008). Most fish screen guidelines in these countries, except New Zealand, were developed to protect migratory salmonids during seaward migration phases (McMichael *et al.* 2004; Moyle & Israel 2005). It is largely accepted, however, that other species impacted by diversions were poorly considered during screen design (Swanson *et al.* 2005). Therefore, screen criteria are now becoming increasingly developed to accommodate nonsalmonid species in an effort to protect other migratory species.

Legislation presently often compulsorily requires irrigation diversion screening in many countries, but owing to 'grandfather' clauses and minimum diversion limits, many structures remain unscreened. In this context, a grandfather clause refers to any existing diversion for which legislative requirements were set at the time of construction. For screens that were constructed many years ago, the impacts of fish would not have been well understood. Present day legislative arrangements, which seek to afford greater protection for fish, can therefore only be applied if a major modification was made. 'Grandfather' clauses therefore prevent screening legislation from being applied to a majority of diversions throughout the United States (Rusak & Mosindy 1997), where diversions are generally small (<5 cfs or 12.2 ml per day) and dated, and owners are not bound to screen (Kepshire 2000). Most water diversions in the Murray–Darling Basin have already been built, so 'grandfather clauses' would generally result in limited uptake of screening technology.

An effective way of promoting fish screen adoption is through development of incentive programmes. In parts of the USA, to encourage voluntary screening, generous financial subsidies of up to 60% of the total cost of design, engineering and installation are offered, in addition to tax concessions (ODFW 2010). So whilst fish screening laws were passed in Oregon as early as 1898, more recently it has been a legislated cost-share programme (begun in 1991), which has seen a rapid and steady uptake of fish screens in the Columbia Basin (Kepshire 2000). Fish screen funding sourced through state lottery revenue has been used to leverage additional irrigator contributions and improve migratory salmonid protection (ODFW 2010). Irrigator contributions can include in-kind labour or materials that reduce the need for individuals to bear substantial construction costs. The overall success of this approach has seen over 50% of all irrigation diversions in Oregon (estimated at over 55 000) fitted with screens in the past century (Kepshire 2000).

Incentives need not be purely monetary in nature. Well-designed screens have the added benefit of reducing fouling and hence maintenance requirements (e.g. by fitting with sprinklers and self-cleaning pumps) and provide additional motivational incentives to screen. Irrigators are also more motivated to install screens when actively involved in the implementation of programmes. The Farmers Conservation Alliance (FCA), a 'not-for-profit group', realised the need to become involved and developed a mandate to help farmers increase the environmental sustainability of profitable agriculture in the USA. It was determined that many farmers were unable to meet legislative requirements of screening laws owing to screen fouling and the high cost of ongoing maintenance. A decade-long research and development programme with irrigators and indigenous groups culminated in the development of creating low-cost screens that have substantially reduced maintenance requirements (Mesa *et al.* 2010). The screen was recently patented, and revenues are now used to create and implement new initiatives that benefit rural communities in collaboration with relevant co-ordinating committees.

Legislation and regulation alone is therefore not enough to create the level of transformational change required to implement large-scale community-based programmes. In the Murray-Darling Basin, it is likely that a mix of legislation and government-funded construction incentives will be needed. For example, existing state legislation requires that any weir modification or refurbishment must also ensure passage for migratory fish is provided. This, combined with significant federal government funding led to an 8-year works and research programme to reinstate fish passage on the Murray River (Barrett *et al.* 2008). In this example, legislation enabled environmental outcomes to be incorporated into infrastructure upgrades and may be a useful funding model for developing future fish screening programmes. There is, however, currently no provision under state or commonwealth legislation that acknowledges water abstraction or diversion as a key threatening process to endangered ecological communities, despite growing evidence to the contrary. Further, whilst strategic government-funded schemes are available to assist irrigators upgrade infrastructure to achieve water efficiency gains, there is currently no capacity for irrigators to access any of this funding to upgrade infrastructure to achieve other environmental benefits, such as fish protection.

So We Built a Screen: Now what Do We Do?

Fish screens operate in hostile environments and are continually exposed to water, sediment and debris. Interference with screen operation through fouling or damage can substantially reduce optimal function (McMichael *et al.* 2004). Ongoing maintenance is therefore a critical aspect of screen effectiveness (Neitzel *et al.* 1990), often necessitating the development of ongoing monitoring and evaluation programmes to ensure maximum screen efficiency, compliance with guidelines and fish protection at times of peak fish migration (McMichael *et al.* 2004). Screen maintenance is seen one of the biggest challenges faced by screening programmes in France (Larinier & Travade 2002; Larinier 2008). Oregon state law requires that government agencies be responsible for screen repair at diversions less than 30 cfs (73.4 ML per day) (Rusak & Mosindy 1997) (ODFW 2010). In New Zealand, screening guidelines acknowledge the need for maintenance and outline requirements for ensuring continual operation performance, but no specific agency or person is responsible for implementation (Jamieson *et al.* 2005). Any fish screening programme in the Murray-Darling Basin will need to establish how ongoing screen maintenance costs will be met, both to gain and maintain irrigator support and to ensure screens continue to protect fish. This is an important consideration that requires definition at early stages of planning.

The Way Forward

There is mounting evidence that irrigation diversions are contributing to the loss of fish from rivers in the Murray-Darling Basin, and solutions to this important conservation issue will need to be found if native fish population declines are to be addressed (Baumgartner *et al.* 2007, 2009; King & O'Connor 2007). A Basin-wide fish screening programme will be the best way to reduce fish losses without compromising the needs of irrigators. Sustainable agriculture is a national issue and should be managed collaboratively by state and commonwealth agencies. Worldwide examples of such programmes are available and could be directly applied to Australian systems.

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References

Allen D. H. (1975) Loss of striped bass eggs and young through small agricultural diversions in Sacramento-San Joaquin Delta. *Californian Department of Fish and Game*, Anadromous Fisheries Branch, Sacramento, CA.

Anon (1997) *Fish Screening Criteria for Anadromous Salmonids*, National Marine Fisheries Service, Santa Rosa.

Anon (2006) *Fish Protection at Water Diversions*. US Department of the Interior, Denver, CO.

Barrett J. (2004) Introducing the Murray-Darling basin native fish strategy and initial steps towards demonstration reaches. *Ecological Management & Restoration* **5**, 15–23.

Barrett J. and Mallen-Cooper M. (2006) The Murray River's 'Sea to Hume Dam' fish passage program: progress to date and lessons learned. *Ecological Management & Restoration* **7**, 173–183.

Barrett J., Baumgartner L. J., Boys C. A., Mallen-Cooper M., Stuart I. G. and Zampatti B. P. (2008) The need for fish passage in the Murray-Darling Basin. In: *The sea to Hume Dam: Restoring fish passage in the Murray River* (ed J. Barrett), pp. 1–11, Murray-Darling Basin Commission, Canberra, ACT.

Baumgartner L. J., Reynoldson N., Cameron L. M. and Stanger J. G. (2007) *The Effects of Selected Irrigation Practices on Fish of the Murray-Darling Basin*. NSW Department of Primary Industries, Cronulla.

Baumgartner L. J., Reynoldson N., Cameron L. M. and Stanger J. G. (2009) Effects of irrigation pumps on riverine fish. *Fisheries Management and Ecology* **16**, 429–437.

Brannon E. S. (1929) *Yakima Basin Ditch Screen Report*. Washington Department of Fisheries, Olympia, WA.

Cadwallader P. and Lawrence B. (1990) Fish. In: *The Murray* (ed D. Mackay), pp. 316–335, Murray-Darling Basin Commision, Canberra, ACT.

Carlson A. J. and Rahel F. J. (2007) A basinwide perspective on entrainment of fish in irrigation canals. *Transactions of the American Fisheries Society* **136**, 1335–1343.

CDFG (2000) *Fish Screen Criteria*. Californian Department of Fish and Game, Sacramento, CA.

Cech J. J. M. and Mussen T. (2006) *Determining How Fish Detect Fish Screens and Testing Potential Fish Screen Enhancements*. California Energy Commission. PIER Energy-Related Environmental Research Program, Sacramento, CA.

Charteris S. C. (2006) *Native Fish Requirements for Water Intakes in Canterbury*. Department of Conservation, Christchurch.

Crabb P. (1997) *Murray-Darling Basin Resources*. Murray-Darling Basin Commission, Canberra, ACT.

Davies N. M., Norris R. H. and Thoms M. C. (2000) Prediction and assessment of local stream habitat features using large-scale catchment characteristics. *Freshwater Biology* **45**, 343–369.

Dayton P. K. (1989) Reversal of the burden of proof in fisheries management. *Science* **279**, 821–822.

Dudgeon D., Arthington A. H., Gessner M. O. *et al.* (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* **81**, 163–182.

Fernando C. H. and Halwart M. (2000) Possibilities for the integration of fish farming into irrigation systems. *Fisheries Management and Ecology* **7**, 45–54.

Gehrke P. C. (1997) Differences in composition and structure of fish communities associated with flow regulation in New South Wales Rivers. In: *Fish and Rivers in Stress: The New South Wales Rivers Survey* (eds J. H. Harris and P. C. Gehrke), pp. 169–200, NSW Fisheries Office of Conservation and the Cooperative Research Centre for Freshwater Ecology, Sydney.

Gilligan D. M. and Schiller C. B. (2003) *Downstream Transport of Larval and Juvenile Fish in the Murray River*. NSW Fisheries, Cronulla.

Gippel C. J. and Collier K. J. (1998) Degradation and rehabilitation of waterways in Australia and New Zealand. In: *Rehabilitation of Rivers: Principles and Implementation* (eds L. C. de Waal, A. R. G. Large and P. M. Wade), pp. 269–300, John Wiley & Sons, Chichester.

Humphries P. and King A. J. (2004) Drifting fish larvae in Murray-Darling Basin rivers: compositions, spatial and temporal patterns and distance drifted. In: *Downstream Movement of Fish in the Murray-Darling Basin. Statements, recommendations and supporting papers from a workshop held in Canberra, 3–4 June 2003* (eds M. Lintermans and B. Phillips), pp. 51–58, Murray-Darling Basin Commission, Canberra, ACT.

Humphries P., Serafini L. G. and King A. J. (2002) River regulation and fish larvae: variation through space and time. *Freshwater Biology* **47**, 1307–1331.

Jacobs T. A. (1990) Regulation and Management of the River Murray. In: *The Murray* (eds J. Mackay and D. Eastburn), pp. 38–58, Murray-Darling Basin Commission, Canberra, ACT.

Jamieson D., Bonnett M., Jellyman D. and Unwin M. (2005) *Fish Screening: Good Practice Guidelines for Canterbury*, NIWA, Auckland.

Kepshire B. (2000) Oregon department of fish and wildlife fish screening program: fish screen types and costs. In: *Salmon Habitat Restoration Cost Workshop* (eds S. T. Allen, C. Thomson and R. Carlson), pp. 1235–1240, Pacific States Marine Fisheries Commission, Gladstone, Oregon.

King A. J. (2002) *Recruitment Ecology of Fish in Floodplain Rivers of the Southern Murray-Darling Basin*, Australia, Monash University, Melbourne.

King A. J. and O'Connor J. P. (2007) Native fish entrapment in irrigation systems: a step towards understanding the significance of the problem. *Ecological Management & Restoration* **8**, 32–37.

Larinier M. (2008) Fish passage experience at small-scale hydro-electric power plants in France. *Hydrobiologia* **609**, 97–108.

Larinier M. and Travade F. (2002) Downstream migration: problems and facilities. *Bulletin français de la pêche et de la pisciculture* **364**, 181–207.

Lintermans M. (2009) *Fishes of the Murray-Darling Basin: An Introductory Guide*, Murray-Darling Basin Authority, Canberra, ACT.

Lintermans M. and Phillips B. (2004) *Downstream Movement of Fish in the Murray-Darling Basin – Workshop Held in Canberra*, 3–4 June 2003: Statement, Recommendations and Supporting Papers. Murray-Darling Basin Commission, Canberra, ACT.

Mallen-Cooper M. (1999) Developing fishways for non-salmonid fishes; a case study from the Murray River in Australia. In: *Innovations in Fish Passage Technology* (ed M. Odeh), pp. 173–195, American Fisheries Society, Bethesda.

Mallen-Cooper M. and Brand D. M. (2007) Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**, 319–332.

McMichael G. A., Vucelick J. A., Abernethy C. S. and Neitzel D. A. (2004) Comparing fish screen performance to physical design criteria. *Fisheries* **29**, 10–16.

MDBC (2003) *Downstream Movement of Fish in the Murray-Darling Basin: Statement, Recommendations and Supporting Papers*, Murray-Darling Basin Commission, Canberra, ACT.

Mesa M. G., Rose B. P. and Copeland E. S. (2010) *Biological Evaluations of an Off-stream Channel, Horizontal Flatplate Fish Screen – The Farmers Screen*, 18 pp. U.S. Geological Survey, Washington.

Moyle P. B. and Israel J. A. (2005) Untested assumptions: effectiveness of screening diversions for conservation of fish populations. *Fisheries* **30**, 20–28.

Moyle P. B. and Williams J. E. (1990) Biodiversity loss in the temperate zone: decline of the native fish fauna of California. *Conservation Biology* **4**, 275–284.

Mueller G. (1996) Establishment of a fish community in the Hayden-Rhodes and Salt-Gila Aqueducts, Arizona. *North American Journal of Fisheries Management* **16**, 795–804.

Musick J., Harbin M., Berkeley S. *et al.* (2000) Marine, estuarine, and diadromous fish stocks at risk of extinction in North America (exclusive of Pacific salmonids). *Fisheries* **25**, 6–30.

Neitzel D. A., Abernethy C. S. and Martenson G. A. (1990) *A Fisheries Evaluation of the Westside Ditch and Town Cala Fish Screening Facilities*, Pacific Northwest National Laboratory, Richland.

NMFS (1997) *Juvenile Fish Screen Criteria for Anadromous Salmonids*. National Marine Fisheries Service, Portland, Oregon. http://swr.nmfs.noaa.gov/hcd/fishscrn.pdf.

Nordlund B. and Bates K. (2000) *Fish Protection Screen Guidelines for Washington State*, 53 pp. Washington Department of Fish and Wildlife, Seattle.

ODFW (2010) *Fish Screening Program. Economic Incentives for Water Users to Protect Fish. 2007–2009 Report to the Legislature*. Oregon Department of fish and Wildlife, Salem, Oregon. http://library.state.or.us/repository/2011/201104081048295/2007-09.pdf.

Parsons M., Thoms M. C. and Norris R. H. (2004) Development of a standardised approach to river habitat assessment in Australia. *Environmental Monitoring and Assessment* **98**, 109–130.

Peake S. (2004) Effect of approach velocity on impingement of juvenile northern pike at water intake screens. *North American Journal of Fisheries Management* **24**, 390–396.

Prince E. E. (1923) Irrigation canals as an aid to fisheries development in the west. *Transactions of the American Fisheries Society* **52**, 157–165.

Redding T. A. (1991) *Fish Production in Irrigation Canals*. Food and Agriculture Organisation, Rome.

Reid D. and Harris J. H. (1997) *New South Wales Inland Fisheries Data Analysis*. Fisheries Research and Development Corporation, Canberra, ACT.

Rusak J. A. and Mosindy T. (1997) Seasonal movements of lake sturgeon in Lake of the Woods and the Rainy River, Ontario. *Canadian Journal of Zoology* **75**, 383–395.

Spaar S. (1994) Delta agricultural diversion evaluation 1992 pilot study. Interagency ecological program for the San Francisco Bay. *Delta Estuary Technical Report* **37**, 37.

Swanson C., Young P. S. and Cech J. J. (2004) Swimming in two-vector flows: performance and behavior of juvenile chinook salmon near a simulated screened water diversion. *Transactions of the American Fisheries Society* **133**, 265–278.

Swanson C., Young P. S. and Cech J. J. (2005) Close encounters with a fish screen: integrating physiological and behavioral results to protect endangered species in exploited ecosystems. *Transactions of the American Fisheries Society* **134**, 1111–1123.

Thoms M. C., Maher S., Terrill P., Crab P., Harris J. and Sheldon F. (2004) Environmental flows in the Darling River. In: *The Darling* (eds R. Breckwoldt, R. Boden and J. Andrew), pp. 350–373, The Murray-Darling Basin Commission, Canberra, ACT.

Turnpenny W. H., Struthers G. and Hanson K. P. (1998) *A UK Guide to Intake Fish-screening Regulations: Policy and Best Practice*. Fawley Laboratories, London.

Unfer G. and Schmutz S. (1998) The course of fish colonisation in the Marchfeldkanal, a man-made canal – the first two years. *Verhandlungen Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* **26**(233), 5–2340.

Vörösmarty C. J., Green P., Salisbury J. and Lammers R. B. (2000) Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288.

Walker K. (1985) A review of the ecological effects of river regulation in Australia. *Hydrobiologia* **125**, 111–129.

White D. K., Swanson C., Young P. S., Cech J. J., Chen Z. Q. and Kavvas M. L. (2007) Close encounters with a fish screen II: delta smelt behavior before and during screen contact. *Transactions of the American Fisheries Society* **136**, 528–538.

Williams J. G. (2008) Mitigating the effects of high-head dams on the Columbia River, USA: experience from the trenches. *Hydrobiologia* **609**, 241–251.

Young W. J. (1999) Hydrological descriptions of semi-arid rivers: an ecological perspective. In: *A Free-flowing River: The Ecology of the Paroo River* (ed R. T. Kingsford), pp. 77–96, National Parks and Wildlife Service, Sydney.

Zydlewski G. B. and Johnson J. R. (2002) Response of Bull trout fry to four types of water diversion screens. *North American Journal of Fisheries Management* **22**, 1276–1282.