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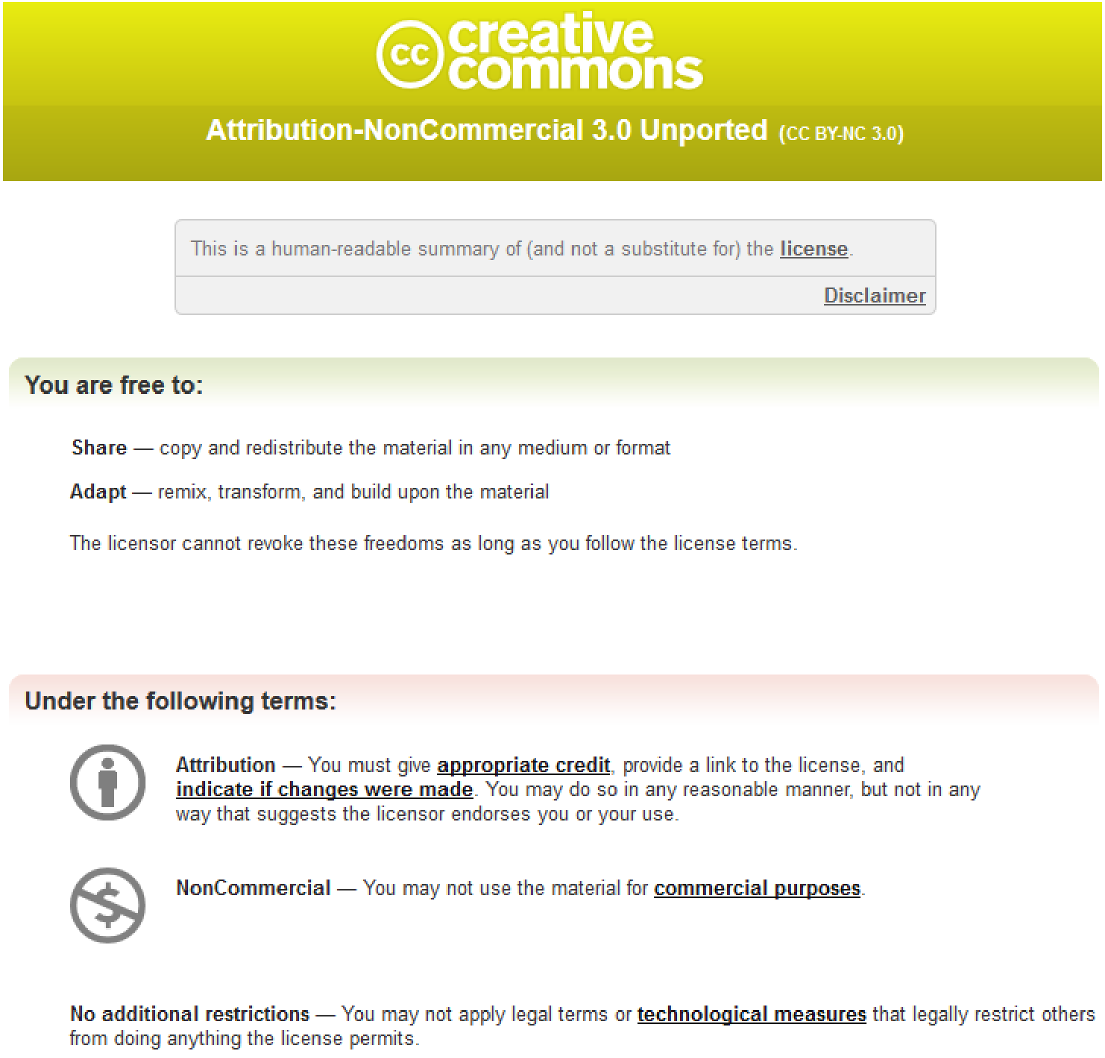

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MANAGEMENT REPORT

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Flows for native fish in the Murray-Darling Basin: lessons and considerations for future management

By John D. Koehn, Alison J. King, Leah Beesley, Craig Copeland, Brenton P. Zampatti and Martin Mallen-Cooper

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Summary **Increased regulation and extraction of water from rivers has contributed to the decline of fishes, and the use of environmental water allocations (EWAs) is now a key rehabilitation measure. Major reform of water policy in the Murray-Darling Basin (MDB), Australia, has recently provided significant EWAs to improve ecological outcomes. Conflict over water buybacks, the value of the water and the need to maximise environmental benefits and minimise risks of unwanted outcomes has increased the expectation for science to underpin and justify such actions. Recent research has focussed attention on the need to understand fish–flow relationships. *The Native Fish Strategy for the Murray-Darling Basin 2003–2013* (NFS), while not specifically targeted at water policy reform or water delivery, has provided fish ecology research and flow restoration experimentation and contributed considerable new scientific knowledge to support flow management. It has contributed to a substantial and positive change in environmental watering for fish, with native fish targets now regularly incorporated into watering objectives. This study documents changes to water management in the MDB, summarises current knowledge of flow-related fish ecology in the MDB, highlights the benefits and risks of some water management practises and provides recommendations for future management and research. A major recommendation is the need for a coordinated, cross-jurisdictional approach to flow restoration for native fish, ensuring that the best available science is being used in all watering allocations. We caution on the use of environmental works such as regulators to artificially inundate floodplains and suggest that such approaches should be viewed as large-scale experiments with the significant risks posed to fish needing to be recognised, adequately monitored and adaptively managed.**

Key words: *rivers, floodplains, environmental water, rehabilitation, restoration, water management.*

Introduction

Alteration of flow regimes is one of the greatest threats to riverine fishes. The construction and management of flow-regulating structures (e.g. dams, weirs and levees) and extraction of water for consumptive use alters the natural flow patterns of rivers, significantly affecting both ecosystem processes and biota (Bunn & Arthington 2002; Vörösmarty *et al.* 2010). This, combined with other threats (e.g. reduced water quality, habitat changes, barriers to connectivity), has resulted in freshwater habitats, and their fishes being among the most threatened in the world (Malmqvist & Rundle 2002; Dudgeon *et al.* 2006). Environmental flows and environmental water allocations (EWAs) are rehabilitation techniques aimed at restoring aspects of the natural flow regime in flow-altered systems, or protecting critical flows in largely unaltered rivers (Arthington *et al.* 2010). An important aspect of such management, however, is understanding the importance of the differing components of flows to fishes.

The Murray-Darling Basin (MDB), in south-eastern Australia, supports much of Australia's food production and is among the world's largest ecosystems impacted by flow regulation (Nilsson *et al.* 2005). High levels of flow regulation and water extraction have significantly contributed to the decline in ecological health of MDB rivers (e.g. Walker & Thoms 1993; Gehrke *et al.* 1995; Davies *et al.* 2010; Kingsford *et al.* 2011). Balancing the use of water for consumptive use against environmental value is also now a major social and political challenge (Poff *et al.* 2003;

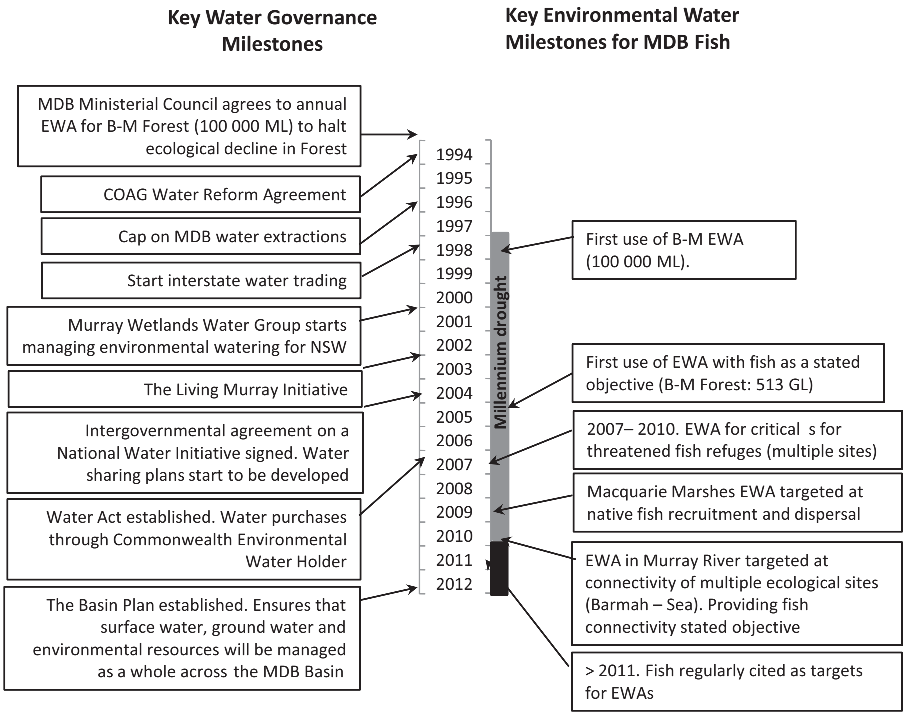

Figure 1. Timeline from 1993 to 2012 illustrating key governance and environmental watering milestones in the Murray-Darling Basin. Drought indicated by grey bar; floods by black bar.

Lester *et al.* 2011; Arthington 2012). This was highlighted during the recent 'millennium drought' in the MDB (1997–2010) (van Dijk *et al.* 2013), where the conflicting water demands for agriculture and the environment were passionately contested (see e.g. http://www.abc.net.au/environment/articles/2012/05/31/3514567.htm).

Like elsewhere in the world, flow regulation in the MDB has been associated with the decline in abundance, distribution and recruitment of native fishes (e.g. Gehrke *et al.* 1995; Humphries *et al.* 2008a,b). The generally poor state of native fishes throughout the Basin led to the development and adoption of a *Native Fish Strategy for the Murray-Darling Basin 2003–2013* (NFS) to rehabilitate their populations (MDBC 2004; Koehn & Lintermans 2012). While there are many threats to MDB fishes (Koehn *et al.* 2014), improved flow regimes and the use of EWAs were seen as a key component of rehabilitation (MDBC 2004). The last decade has seen a rapid expansion in the allocation and management of water for the environment in the MDB. This has occurred through programmes, such as the National Water Initiative, The Living Murray programme and more recently development of the Murray-Darling Basin Plan and establishment of Commonwealth Environmental Water Office. The Basin Plan has been a divisive political issue, but a common goal of 'a healthy fish community' can help to reconnect disparate sectors of both management and rural communities (Koehn 2013). While the NFS did not directly 'buy' or 'manage' water for fish rehabilitation, it did make significant contributions to the generation and exchange of knowledge among scientists and managers to underpin EWA management, as well as the promotion to water managers of the needs of fish.

This study describes some of the advances made towards improving flow management for positive native fish outcomes in the MDB in relation to their contribution to the objectives of the NFS (see Koehn *et al.* 2014). In particular, we (i) document past and present water management that has influenced fishes; (ii) describe the importance of different flow components for fishes; (iii) highlight risks to native fish from artificial floodplain inundation projects; and (iv) provide a series of recommendations to direct the future management of flows to benefit native fishes in the MDB.

Water Management in The MDB

Under the Australian Constitution, State Governments are responsible for the management of most natural resources, including water. The State and Federal governments have collectively managed water in the Basin since 1915, following the formation of the River Murray Commission, which was charged with operating all of the dams and weirs in the Murray River and Lower Darling River. Water storage capacity grew substantially from <1000 GL in 1927 to 30,000 GL in 1980 (Blackmore 1995). Increased water abstraction also coincided with increasing public and scientific concerns over the ecological health of the Basin and the impacts of river regulation (e.g. Cadwallader 1978; Lloyd & Walker 1986; Walker & Thoms 1993). In 1967, the first EWA for the MDB was granted, with a Wild Life Allocation of approximately 18.5 GL for the Macquarie Marshes, New South Wales, to address declines in waterbird breeding. An initial allocation of 18.5 GL was delivered in 1980, followed by another 50 GL in 1983 (Fig. 1) (Milligan & Cottingham 2009). As an amelioration measure after the construction of Dartmouth Dam, the Murray River received its first EWA in 1979, with the Murray Flora and Fauna Bulk Entitlement (27.6 GL/year) targeting northern Victorian wetlands. In 1993, all MDB States authorised an additional 100 GL as an annual EWA for Barmah–Millewa Forest (B–M), which could be carried over to create a larger volume if required; the first EWA for B-M being delivered in 1998 (Fig. 1; Ward & Colloff 2010). In 1994, the Council of Australian Governments (COAG) agreed to a landmark water reform framework which capped surface water extraction to 1993–1994 levels, recognised the environment as a legitimate water user and allowed the transfer of water rights for environmental purposes (COAG 1994; Garrick *et al.* 2009). The *NSW Water Management Act 2000* and *Queensland Water Act 2000* enabled Water Sharing/Resource Plans or Water Plans, which specifically considered environmental needs for each subcatchment and in Victoria and South Australia the

Water (Resource Management) Act 2005 and *Natural Resources Management Act 2004*, respectively, formalised Stream Flow Management Plans and Water Allocation Plans.

In 2004, the National Water Initiative aimed to integrate water management for both economic and environmental outcomes (Milligan & Cottingham 2009), and the Federal *Water Act,* 2007, established the Murray-Darling Basin Authority, the Commonwealth Environmental Water Holder and subsequently the Basin Plan. This was the biggest potential change in water management in the MDB since 1915, involving $3.1 billion (Aus) to improve infrastructure, buyback water licences and increase water for the environment (MDBA 2010, 2011). Ultimately, the above programmes and legislation resulted in water being returned to the environment in two forms: (i) 'planned' or 'rules' based, where Water Management Plans stipulate how water is to be managed in different river valleys, for example restricting water access to irrigators, imposing total extraction limits or requiring a proportion of dam inflows to be passed downstream; and (ii) Adaptive Environmental Water, where water that has been purchased is used for a specified environmental purpose. The number of applications and the volumes of EWA used in the MDB have rapidly increased over the last two decades (see Fig. 2, Table S1).

Prior to 2005, no EWAs targeted native fish outcomes to our knowledge (See Fig. 2 and EWA descriptions in Table S1). This is likely to be due to the limited knowledge of flow characteristics that may have benefited native fish; the focus on other more obvious declines in system health, such as waterbird breeding and vegetation condition; and priority attention given to internationally recognised floodplain wetlands such as the Gwydir Wetlands, Macquarie Marshes and B-M. While it is likely that many EWAs would also have benefited native fish, it was not until 2005 that objectives for native fish were explicitly outlined in the EWA for B-M (see text Box 1; King *et al.* 2010).

Initially, environmental watering objectives were focussed on single species, small groups of species (e.g. nesting waterbirds) or sites and were generic; for example, 'to provide habitat for waterbirds'; but have now changed to recognise the breadth of biota (e.g. macroinvertebrates, fish, frogs, turtles, aquatic vegetation, terrestrial vegetation, biofilms), geomorphology and ecosystem processes such as connectivity, energy production, recruitment and resilience. The improvement in ecological objective setting and justification for EWAs have been greatly assisted by the many studies (including those of the NFS; Table S2; see also Koehn & Lintermans 2012; Koehn *et al.* 2014) that provided key new ecological knowledge at a critical period in environmental water management. The NFS facilitated the exchange of information among scientists and managers and promoted fish as an important biota that the community could relate to (see Hames *et al.* 2014). It also directly contributed to environmental flow research and monitoring activities, including the spawning, recruitment and lateral movement of fish before and after the B-M 2005/2006 EWA (see case study; Jones 2007; King *et al.* 2007, 2009, 2010); the importance of small flows to maintain refuge pools for fish during drought in the Wakool River (Gilligan *et al.* 2009); and the impacts of managed flows on fish spawning (Humphries *et al.* 2008a,b, 2012). Importantly, the NFS also highlighted the risks to native fishes of impounding water on floodplains using the new strategy of Environmental Works and Measures such as regulators and promoted the need for monitoring to support adaptive management of these structures (see case study Box 2 and later discussion; Mallen-Cooper *et al.* 2008, 2011).

Box 1. Allocating environmental water for multiple ecological outcomes in the Barmah–Millewa Forest

Barmah–Millewa Forest is a large, complex floodplain wetland system in the mid-Murray River, which is listed as internationally important under the Ramsar convention, and is an icon site for The Living Murray Initiative. Flow regulation has affected the natural flooding and drying cycles of the Forest, resulting in a decline of its ecological integrity. An EWA of up to 150 GL per year is specifically allocated to B-M, with limited carry-over between years. B-M has a long history of water management with numerous levee banks and regulators. EWAs have been used in the 1990s and early 2000s, targeting waterbird breeding and watering of key vegetation. In 2005/2006, 513 GL of the B-M EWA was used to 'piggyback' natural flow peak to increase its magnitude and duration. The EWA aimed to achieve multiple ecological objectives for vegetation, waterbirds, frogs and to enhance breeding and recruitment of native fish. This included incorporating specific variation in the managed flows to attempt to trigger Golden Perch and Silver Perch spawning and movement. This management event proved to be highly successful with the occurrence of enhanced growth and health of significant native vegetation species; a highly significant waterbird breeding event (>52,000 individuals of a number of species), successful breeding of frogs, significant nutrient and carbon input into the river channel and enhanced spawning and/or recruitment of several significant native fish species: Golden Perch, Silver Perch, Murray Cod, Trout Cod and Southern Pygmy Perch (see King *et al.* 2010 for more details). Concurrent research also demonstrated that the 2005/2006 B-M EWA allocation had positive outcomes for native fish at other significant sites downstream (Vilizzi 2012), including Golden Perch recruitment in the lower Murray River in South Australia (Zampatti & Leigh 2013b).

Box 2. Chowilla case study

The Chowilla Anabranch system is the largest area of undeveloped floodplain in the lower River Murray. It is listed under the Ramsar Convention and is an Icon Site of the Living Murray Initiative. The Chowilla floodplain is a complex of perennial and ephemeral creeks, backwaters, billabongs and lakes and contains significant River Red Gum (*Eucalyptus camaldulensis*) and Black Box (*Eucalyptus macrocarpa*) woodlands. Chowilla bypasses Lock and Weir No. 6 and has permanent lotic habitats once characteristic of the historically unregulated River Murray in a region where serial main-channel weirs have created predominantly permanent lentic habitats (Walker 2006). The unique flowing water habitats of Chowilla support regionally significant populations of Murray Cod and high abundances of other species such as Golden Perch (Zampatti *et al.* 2011). The floodplain system, however, has become increasingly degraded as a consequence of changes to the natural flow regime, hydraulic pressure from the adjoining weir pool permanently raising the water table, grazing and drought (MDBC 2006). To maintain or improve the health of existing areas of River Red Gum and Black Box, a large (79 m wide, 3 m head-differential) regulator is being constructed on lower Chowilla Creek to artificially inundate the floodplain for one to three months during spring every one to five years, depending on floodplain condition. This period of operation directly overlaps with the major season of native fish spawning. Such artificial floodplain inundation presents substantial risks to native fish, primarily threatened Murray Cod and Freshwater Catfish but also Golden Perch and Silver Perch, while also constituting a high risk of the proliferation of Common Carp (Mallen-Cooper *et al.* 2008, 2011). Indeed, using a regulator potentially creates large areas of lentic habitat, replicating the features of weir pools in the River Murray that have led to wholesale ecological change in that river (Walker 2006). Operation of this regulator, due to commence in late 2014, represents an unparalleled experiment in lowland river restoration and requires robustly designed monitoring and responsive adaptive management to elucidate ecological outcomes and mitigate risks to fish. Similar regulators are proposed for operation at three additional anabranch systems in the lower River Murray (Lindsay–Mullaroo, Katarapko and Pike River) which is likely to compound impacts on fishes at a larger scale.

Importance of Flows for Fish in the MDB

Flows and riverine fishes are inherently linked, and most studies on freshwater fish in the Murray-Darling Basin include reference to flows. The need to provide specific guidance on environmental flows for fishes in the Basin has been formally recognised since the mid-1980s (e.g. Richardson 1986; Swales & Harris 1995). Early approaches were either ‘top down’ using hydrological measures or ‘bottom up’ describing the physical nature and hydraulics of habitats, and the flows required to achieve habitat thresholds. Both approaches ultimately require knowledge of fish behaviour and ecology for their application. A review of the importance of flows for MDB fishes (Humphries *et al.* 1999) highlighted the inadequacy of our knowledge to underpin the emerging area of EWAs for fish. This review, discussions on native fish issues within the MDB (e.g. NFS and the Living Murray programmes), and a growing urgency for improved ecological outcomes with limited water, prompted increased research in flow-related fish ecology. The summary below describes the main research outcomes during this period and demonstrates the value of EWAs for fish. It relies heavily upon knowledge generated in the southern MDB, particularly the Murray River, where most research has been conducted, but does include northern examples where appropriate. From our experience, however, significant variation exists across species and regions, and general extrapolations are unwise and risky. Benefits, risks and limitations of EWAs and other water management options for fish are summarised in Table S2. Recognition of the impacts of flow components on the various requirements of different species and life stages is essential for management, as in flow-altered rivers, many of the components essential to fishes have already been reduced or lost, for example reduced flooding and floodplain habitats, reduced flow variability and cues for movements or reproduction.

Flows and habitats

Spatial complexity in hydraulic characteristics (i.e. velocity, depth and turbulence) provides habitat heterogeneity and promotes biological diversity (Dyer & Thoms 2006). River regulation in the MDB alters the hydraulic nature of flow in two ways that have impacts on fishes: (i) in the mid–upper reaches of the Murray River, fish that require low flow areas for nursery habitats in summer are disadvantaged by high volume, high velocity irrigation flows (Humphries *et al.* 2006) and (ii) weir pool environments in the lower Murray disadvantage species whose life histories require lotic habitats (e.g. Murray Cod *Maccullochella peelii*; Koehn 2009)) and favour lentic species (such as Common Carp *Cyprinus carpio*) (Walker 2006).

The high spatial and temporal diversity of inundated floodplain habitats supports a high diversity of fauna, including fish (Ward & Stanford 1995). A number of MDB fish utilise floodplain habitats and

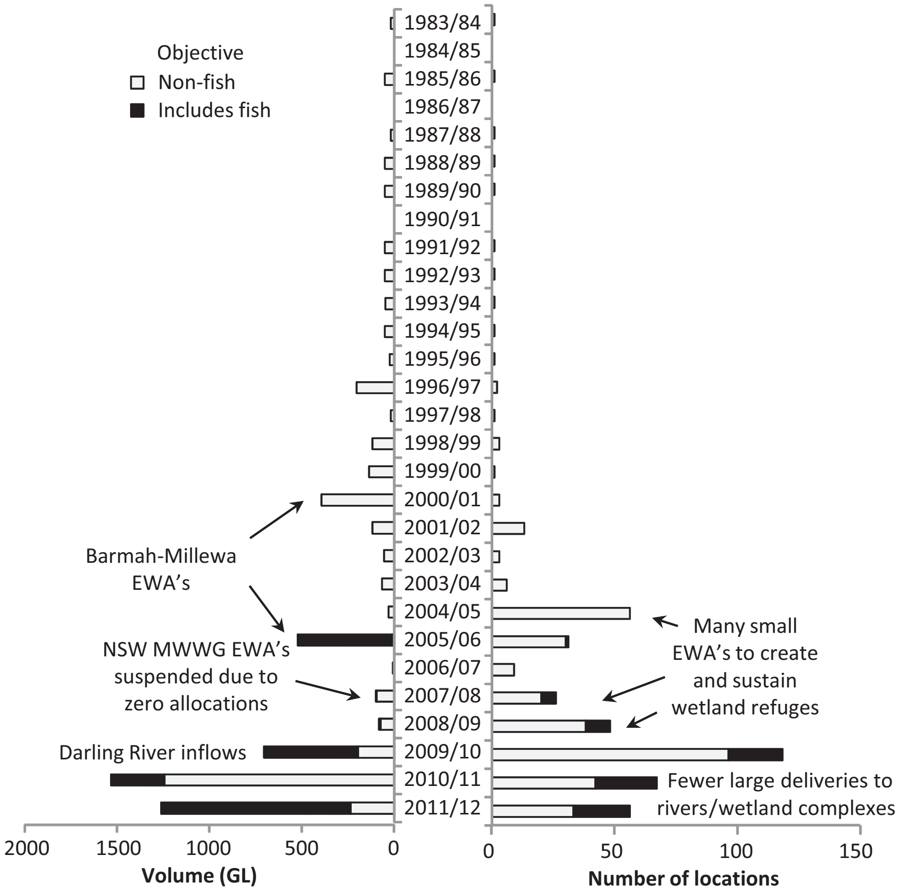

Figure 2. Total volume and number of environmental water allocations for the Murray-Darling Basin from 1983 to 2012. MWWG, Murray Wetlands Working Group; EWA, Environmental Water Allocation.

channels, particularly on a temporary basis during flooding (e.g. Rolls & Wilson 2010), but only a few species are considered to be 'wetland specialists' (Macdonald *et al.* 2012). Indeed, the decline of wetland species such as Murray hardyhead (*Craterocephalus fluviatilis*), Olive Perchlet (*Ambassis agassizii*) and Southern Purple-spotted Gudgeon (*Mogurnda adspersa*) may be a consequence of the decline in regular flooding (Hammer *et al.* 2013) and a loss of floodplain habitats (Kingsford & Thomas 2004). For such species, EWAs can maintain wetland habitats and drought refugia (Gilligan *et al.* 2009; Rayner *et al.* 2009). This was particularly highlighted during the millennium drought, when EWAs were successfully used to prevent individual wetlands from drying and to maintain refuges for threatened wetland specialist species such as Murray Hardyhead and Southern Pygmy Perch (*Nannoperca australis*) (Hammer *et al.* 2013).

Flows and productivity

Large flows (floods) that inundate floodplains, or intermediate flows that inundate in-channel benches are fundamental to the processing and exchange of nutrients and organic matter between a river and its surrounds (Junk *et al.* 1989; Tockner *et al.* 2000). Some fish species use inundated, food-rich floodplains to improve body condition and growth (e.g. Bony Bream *Nematalosa erebi*, Golden Perch *Macquaria ambigua* and Carp Gudgeon *Hypseleotris* spp.; Balcombe *et al.* 2012; Beesley *et al.* 2011, 2012) while others, such as Australian Smelt (*Retropinna semoni*), can increase growth and condition under a range of flows (Tonkin *et al.* 2011). Floodplain inundation has also recently been shown to be critical for maintaining riverine fish production in Australian tropical river systems (Jardine *et al.* 2012), but little is known about this in the MDB and further research is warranted.

While much of the scientific research on flows and fish in the MDB has been conducted at the level of a specific event, flow events do not occur in isolation. Antecedent conditions are the hydrological characteristics that aquatic biota and their habitats are exposed to prior to the hydrological event of interest (Rolls *et al.* 2012). Antecedent flows influence the characteristics of the pre-existing fish assemblage, hence affect how it responds to proximate flow events (Biggs *et al.* 2005). For example, the recruitment and body condition of Golden Perch and Bony Bream in waterholes in a northern MDB river were greater when the river had previously received a flow pulse (Balcombe *et al.* 2012). Similarly, growth rates of juvenile Australian Smelt in the Ovens River were related not only to current flow and temperature, but also to the occurrence and duration of prior flood events (Tonkin *et al.* 2011).

Flows and reproduction

Elsewhere in the world, regular flooding is known to enhance fish recruitment, as it cues spawning and/or increases the availability and access to food for young fish, hence improving their growth and survival (Junk *et al.* 1989). The importance of flooding to fish spawning and recruitment in the MDB, however, is less clear (Humphries *et al.* 1999) and is dependent on species' life-history strategy and aspects of the hydrological regime (principally timing, duration and frequency) (King *et al.* 2003). For example, appropriately, timed flows (both floods and within-channel variations) have been linked to increased spawning and recruitment for Golden Perch and Silver Perch (*Bidyanus bidyanus*) (Mallen-Cooper & Stuart 2003; King *et al.* 2009; Zampatti & Leigh 2013a,b), but both species appear to be highly flexible and can also spawn irrespective of flow in some locations (Balcombe *et al.* 2006; Ebner *et al.* 2009). Murray Cod and Trout Cod (*Maccullochella macquariensis*) spawn annually, independent of flow (e.g. Humphries 2005; Koehn

& Harrington 2006), but recruitment may be enhanced during floods (Ye *et al.* 2000; King *et al.* 2009). Longer duration river–wetland connections also increase the abundance of young-of-the-year fish in wetlands, in particular Carp Gudgeon and the alien Common Carp (Beesley *et al.* 2012; Conallin *et al.* 2012). Small within-channel EWAs have also been shown to increase recruitment and species richness, but natives were outnumbered 3:1 by alien fish (Rayner *et al.* 2009).

While much emphasis was previously placed on the importance of flooding for spawning and recruitment of MDB fishes (e.g. Harris & Gehrke 1994), the 'Low Flow Recruitment Hypothesis' proposed that some fishes breed successfully during summer low flows, utilising still and slow-water habitats (or slackwaters) that are warmer and contain higher concentrations of prey (Humphries *et al.* 1999). These habitats have been shown to support the spawning and rearing of typically smaller, short-lived fish species (Humphries *et al.* 2006) such as Australian Smelt, Carp Gudgeon and Eastern Gambusia (*Gambusia holbrooki*) (King 2004).

Flows and movements

Flow pulses, especially in spring and summer, stimulate adult and juvenile fish to move both upstream and/or downstream to spawn or exploit alternative habitats (Mallen-Cooper 1999; Mallen-Cooper & Brand 2007). Murray Cod generally display localised movements (Koehn *et al.* 2009) but may move large distances, especially in association with floods (e.g. Reynolds 1983; Leigh & Zampatti 2013). In the mid-Murray River, immature Golden Perch and Silver Perch can numerically dominate migratory populations and have staged upstream movements over a long period, consistently moving in response to small increases in flow (Mallen-Cooper & Brand 2007). During autumn and winter, however, such changes result in minimal fish movement through fishways (Mallen-Cooper 1999). Not all movement occurs during higher flows, with some small-bodied fish such as Carp Gudgeon, Murray-Darling Rainbowfish (*Melanotaenia fluviatilis*) and Unspecked Hardyhead (*Craterocephalus stercusmuscarum fulvus*) moving in large numbers during lower flow periods (Stuart *et al.* 2008). Early life stages of fish may actively and passively utilise flow pulses for dispersal from the breeding site (Humphries & King 2004). Flow-facilitated dispersal not only enables species to increase their distribution, but mixing of fish among catchments or subcatchments increases genetic diversity. For example, Golden Perch have greater genetic diversity in catchments with greater spring flows due to increased fish dispersal (Faulks *et al.* 2010).

Small-bodied fish (e.g. Carp Gudgeon) may actively move onto floodplain habitats during rising flows and then back to the river channel during falling flows (Lyon *et al.* 2010), potentially capitalising on the food and habitat rich floodplain, while minimising the risk of stranding. There is also emerging evidence that the timing and duration of river–floodplain connection affects the timing of fish movement, with Common Carp and Bony Bream moving relatively quickly upon connection (Conallin *et al.* 2012), but other species such as Unspecked Hardyhead and Freshwater Catfish (*Tandanus tandanus*) waiting weeks (Rick Stoffels pers. comm.). There is little direct information on the lateral movements of large-bodied native fish, although this is likely to occur at least between anabranches or creek lines and the main channel. For example, adult Golden Perch utilise temporarily inundated floodplain habitats in the lower River Murray (Brenton Zampatti unpubl. data) and consistently move between the main channel and perennially inundated wetlands (Conallin *et al.* 2011). Murray Cod, however, generally do not move onto the floodplain proper, but do use floodplain creeks and anabranches when they are flowing (Jones & Stuart 2008; Koehn *et al.* 2009; Leigh & Zampatti 2013).

Flows to estuaries

Estuaries form a dynamic interface between marine and freshwater environments where freshwater flows and tides determine salinity, and influence fish assemblage structure and recruitment of many marine, estuarine, freshwater and diadromous fishes (Gillanders & Kingsford 2002). Fish assemblages in the Murray River estuary (the Coorong) are most diverse when freshwater inflows create brackish conditions and facilitate connectivity between the freshwater Lower Lakes and Coorong (Zampatti *et al.* 2010). In the absence of freshwater inputs, as occurred from 2007 to 2010, salinities in the Coorong trend to marine–hypersaline, fish species richness and diversity decrease, freshwater and diadromous species become less abundant and the recruitment of diadromous species fails (e.g. Congolli *Pseudaphritis urvillii*; Zampatti *et al.* 2010).

Risks and Limitations

While flooding can provide many benefits to native fishes, managed flows may also create negative outcomes. Flooding has been linked to increased recruitment and dispersal of alien fishes such as Common Carp, Oriental Weatherloach (*Misgurnus anguillicaudatus*) and Eastern Gambusia (Stuart & Jones 2006; Beesley *et al.* 2012). Summer floods can create hypoxic blackwater events that can lead to fish kills (King *et al.* 2012; Beesley *et al.* 2013; Leigh & Zampatti 2013) and may also contribute high levels of sedimentation (Lyon & O'Connor 2008). EWAs need to consider these risks, but there are also opportunities for EWAs to assist in risk mitigation. For example, EWAs can be targeted at reducing the risk of reduced dissolved oxygen (hypoxia) associated with blackwater, eutrophication and pH issues associated with acid sulfate soils (see Supplementary Table 1).

Since the early 2000s, there has been an increased emphasis along the Murray River on the construction and use of infrastructure such as pumps and regulators to apply water for environmental purposes (Pittock *et al.* 2013). Under drought conditions, the emphasis on EWAs was to maximise the floodplain area watered for the volume of water used.

While impounding water on the floodplain may benefit some plants and biota, the benefits for fish are less certain. Impounding water is not the same as a flood; there are many differences and considerable risks for fishes (see Chowilla case study, text Box 1); Mallen-Cooper *et al.* 2008, 2011). Impounded water backs up from downstream, increases floodplain residency times, is confined to a narrower floodplain area and changes flow patterns, diversity and velocities, converting flowing to still waters. Furthermore, regulators and levees will inhibit fish passage. These factors may result in an increased likelihood of poor water quality or blackwater (King *et al.* 2012), increased production of Common Carp (Bice & Zampatti 2011), decreased recruitment of native fish reliant on lotic environments such as Murray Cod (Mallen-Cooper *et al.* 2008) and potential fish stranding (Jones & Stuart 2008). These constraints and risks to fish need to be carefully considered when using these structures in conjunction with EWAs.

Table 1. Recommendations for the future management of flows for fishes in the MDB

Recommendations
Management
• **Establish an Environmental Flows and Fish Reference Group** that includes fish ecologists, site-specific water managers, river operators and water policy representatives with the aims to exchange knowledge and provide alternative watering scenarios for key sites. Convene a forum to provide general recommendations for flow management and assist in incorporating this knowledge into water management plans.
• **Undertake environmental watering at spatial scales applicable for fish.** Maximise multisite, longitudinal benefits of any EWA by ensuring its status is 'green to the sea' (i.e. being protected as water for environmental objectives, not for extraction).
• **Link flow management to other rehabilitation actions** and ensure the appropriate flows are provided to support their success (e.g. flows to operate fishways; see Baumgartner *et al.* 2014)
• **Ensure appropriate water quality for all EWAs** (e.g. temperature for native fish spawning; Sherman *et al.* 2007)
• **Coordinate cross-jurisdictional approaches** that will ensure the most effective outcomes from science, monitoring and management in conjunction with State-based programmes
• **Incorporate specific fish-flow objectives** for all key sites and river reaches
• **Optimise environmental watering objectives by including benefits to all biotic groups**
• **Include climate change predictions** in water management
• **Use experimental adaptive management approaches** to learn from management actions
Knowledge
• **Clarify the responsibility for provision of adequate ecological knowledge** for water management and commit to funding long-term, high-quality science to support evidence-based management
• **Undertake targeted and long-term monitoring** over a range of flow conditions to determine the causal mechanisms of how fish respond to flows. Standard 'surveillance' monitoring is not sufficient for this purpose.
• **Undertake additional ecological studies in the north of the MDB** and apply this knowledge at the appropriately comparable biogeographic and hydrological sites rather than extrapolating from Murray River studies
• **Further study fish responses to key aspects of the flow regime** so that this knowledge can be used to maximise benefits to native fish populations
• **Understand the needs of fish** in the context of flow regimes over longer time frames at landscape scales and via ecological processes
Impounding waters
• **Artificially inundating floodplains by environmental works and measures such as regulators should be recognised as large-scale experiments** that pose risks to fish (e.g. altered hydrodynamics, poor water quality, barriers to movement, reduced recruitment for some native species, increased recruitment for alien fish species). Given the significant level of risks of existing structures for fish, there is a need to evaluate the consequences of their impacts before additional structures are commissioned
• **Develop and use conceptual models of floodplain ecosystems and biota** to direct research, management and monitoring. Such models can be refined as more data become available
• **Include adequate biotic (fish) monitoring components into works and measures budgets** so that the implications of the works and operations can be adequately quantified
Community understanding and support
• **Engender a positive public perception of the benefits of environmental watering for fish,** including the incorporation of recreational anglers and conservation organisations as key stakeholders
• **Increase public knowledge of the need for flows for fish-build** on existing work established by the NFS
• **Fish should be included as assets** recognised in the operation of the Basin Plan

Future Directions and Challenges

Providing benefits for native fish populations through the use future of EWAs requires learning from past experiences to address the significant challenges posed. Below, we explore the main challenges that we see in this area and provide key recommendations in Table 1.

Management

There have been major changes to flow management in the MDB in recent decades, including a substantial increase in the availability of environmental water and more ecologically sensitive management of regulated flows. Many early EWAs provided outcomes for native fish that were either unintentional (EWAs targeted at other ecological outcomes) or were for specific purposes, such as maintenance of refuge habitats, often in response to the severe drought. We now have the opportunity to move towards managing flows in the context of flow regimes over longer time frames and larger spatial scales, and there is an increased need and expectation to utilise up-to-date knowledge to underpin EWAs. Establishing an environmental flows fish reference group that includes fish ecologists, water managers and river operations managers would be an important first step in integrating science and management/operations to maximise ecological outcomes for fish. We suggest that the implementation of the Basin Plan is an opportune time to establish such a group. Opportunities must also be taken to manage flows at the 'river-scape' scale rather than just on a single-site basis, maximising multisite and longitudinal benefits of EWAs ensuring their environmental water status as 'green to the sea' (i.e. being protected as water for environmental objectives, not for extraction from source, through the target site and out to the sea). As a result of predicted reductions in run-off and more extreme drought and floods due to climate change, there will be increasing pressure on the use of EWAs (CSIRO 2008). Climate change will have a wide range of impacts on fishes and their habitats (Koehn *et al.* 2011), and while this needs to be factored into future water management (Aldous *et al.* 2011), in reality, the reductions in flows are minor compared to those already imposed by river regulation and water extraction (McMahon & Finlayson 2003).

Environmental works and measures projects, such as the construction and use of regulators to artificially inundate floodplains, should be recognised as large-scale experiments that pose risks to fish and other aquatic biota. The cumulative impacts of these structures need to be quantified across broader spatial scales, and the consequences evaluated before additional structures are commissioned.

Knowledge

Given the commitment to the Basin Plan and increasing volumes of EWAs, there will be greater public scrutiny of such allocations and an expectation to demonstrate wise use and delivery to maximise environmental benefits. Managing flows must now be undertaken in a more comprehensive manner, with the use of best available science and knowledge. Less water and greater expectations for positive environmental outcomes increase the need for improved ecological knowledge. While there have been major advances in our scientific knowledge of fishes, our understanding of how to allocate water to best achieve native fish outcomes is in its infancy. We need to better understand flow regimes and their various components and how these relate to the life history and population dynamics of fish. There is a need to commit to undertake quality research through coordinated (not *ad hoc* or piecemeal) studies that answer key questions. This may include targeted and long-term monitoring over a range of flow conditions at specific sites or manipulative experiments to determine the causal mechanisms of how fish respond to flows. Standard 'surveillance' or 'condition' monitoring, such as the Sustainable Rivers Audit (Davies *et al.* 2010) or yearly assessments, does not allow change to be attributed to any one cause and are usually insufficient for this purpose.

Community understanding and support

The Basin Plan has been a divisive social and political issue, but a common goal of 'a healthy fish community' can help to reconnect disparate sectors of the rural community. Indeed, the status of fish populations, especially angling species, is the single measure by which the public is most likely to judge the successful management of rivers and water in the MDB (Koehn 2013). Engaging a positive public perception of the benefits of EWAs for fish, including the incorporation of recreational anglers and conservation organisations as key stakeholders, could bring substantial benefits to the environmental water debate (Mainstone *et al.* 2012). The NFS has undertaken a wide range of activities that create community support for MDB fishes (Hames *et al.* 2014), and many of these could assist the promotion of the benefit of environmental flows.

Conclusion

The new intensive water management in the MDB means that significantly more water (> 1000 Gl) is now available to deliver environmental outcomes. Competing demands and the cost of the water, particularly under the pressures of droughts and climate change, increases in populations and food production, places an even greater focus on wise use of EWAs to maximise ecological outcomes, including sustaining and enhancing native fish populations. For this to occur, managers must have access to the best available science, which, along with environmental flow management and research, has improved in recent years. An adaptive management approach is critical to the advancement of environmental flow management, and we suggest that future EWAs are underpinned by a strong conceptual understanding of aquatic ecosystems and linked to scientifically rigorous monitoring and research that includes native fish as a core indicator.

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References

Aldous A., Fitzsimons J., Richter B. and Bach L. (2011) Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research* **62**, 223–231.

Arthington A. H. (2012) *Environmental Flows. Saving Rivers in the Third Millennium*. University of California Press, Berkeley.

Arthington A., Naiman R. J., McClain M. E. and Nilsson C. (2010) Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology* **55**, 1–16.

Balcombe S. R., Arthington A. H., Foster N. D., Thorns M. C., Wilson G. G. and Bunn S. E. (2006) Fish assemblages of an Australian dryland river: abundance, assemblage structure and recruitment patterns in the Warrego River, Murray-Darling Basin. *Marine and Freshwater Research* **57**, 619–633.

Balcombe S. R., Lobegeiger J. S., Marshall S. M., Marshall J. C., Ly D. and Jones D. N. (2012) Fish body condition and recruitment success reflect antecedent flows in an Australian dryland river. *Fisheries Science* **78**, 841–847.

Baumgartner L., Zampatti B., Jones M., Stuart I. and Mallen-Cooper M. (2014) Fish passage in the Murray–Darling Basin, Australia: Not just an upstream battle. *Ecological Management & Restoration* **15** (Suppl. 1), 28–39.

Beesley L., Price A., King A. *et al.* (2011) *Watering Floodplain Wetlands in the Murray-Darling Basin for Native Fish, Waterlines Report*. National Water Commission, Canberra, Australia.

Beesley L., King A. J., Amtstaetter F. *et al.* (2012) Does flooding affect spatiotemporal variation of fish assemblages in temperate floodplain wetlands? *Freshwater Biology* **57**, 2230–2246.

Beesley L., McCarthy B., Acevedo S. *et al.* (2013) The response of aquatic taxa to hypoxic blackwater in the southern Murray-Darling Basin. Arthur Rylah Institute for Environmental Research, Unpublished technical report. Department of Environment and Primary Industries. Heidelberg, Victoria.

Bice C. M. and Zampatti B. P. (2011) Engineered water level management facilitates recruitment of non-native common carp, *Cyprinus carpio*, in a regulated lowland river. *Ecological Engineering* **37**, 1901–1904.

Biggs B. J. F., Nikora V. L. and Snelder T. H. (2005) Linking scales of flow variability to lotic ecosystem structure and function. *River Research and Applications* **21**, 283–298.

Blackmore D. J. (1995) Murray-Darling Basin Commission: a case study in integrated catchment management. *Water Science and Technology* **32**, 15–25.

Bunn S. E. and Arthington A. H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30**, 492–507.

Cadwallader P. L. (1978) Some causes of the decline in range and abundance of native fish in the Murray-Darling river system. *Proceedings of the Royal Society of Victoria* **90**, 211–224.

COAG (1994) Communique. Meeting 25 February 1994 Viewed at http://www.archive.coag.gov.au/coag_meeting_outcomes/1994-02-25/index.cfm accessed August 2013

Conallin A. J., Hillyard K. A., Walker K. F., Gillanders B. M. and Smith B. B. (2011) Off stream movements of fish during a drought in a regulated lowland river. *River Research and Applications* **27**, 1237–1252.

Conallin A. J., Smith B. B., Thwaites L. A., Walker K. F. and Gillanders B. M. (2012) Environmental Water Allocations in regulated lowland rivers may encourage offstream movements and spawning by common carp, *Cyprinus carpio*: implications for wetland rehabilitation. *Marine and Freshwater Research* **63**, 865–877.

CSIRO (2008) *Water Availability in The Murray-Darling Basin. Summary of a Report From CSIRO to the Australian Government*. CSIRO, Canberra. [Accessed 2 February 2013.] Available from URL: http://www.csiro.au/files/files/pna0.pdf.

Davies P. E., Harris J. H., Hillman T. J. and Walker K. F. (2010) The Sustainable Rivers Audit: assessing river ecosystem health in the Murray-Darling Basin. *Australia. Marine and Freshwater Research* **61**, 764–777.

van Dijk A. I. J. M., Beck H. E., Crosbie R. S. *et al.* (2013) The millennium drought in southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources and Research* **49**, 1040–1057.

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

Dyer F. J. and Thoms M. C. (2006) Managing river flows for hydraulic diversity: an example of an upland regulated gravel-bed river. *River Research and Applications* **22**, 257–267.

Ebner B., Scholz O. and Gawne B. (2009) Golden perch *Macquaria ambigua* are flexible spawners in the Darling River, Australia. *New Zealand Journal of Marine and Freshwater Research* **43**, 571–578.

Faulks L. K., Gilligan D. M. and Beheregaray L. B. (2010) Islands of water in a sea of dry land: hydrological regime predicts genetic diversity and dispersal in a widespread fish from Australia's arid zone, the golden perch (*Macquaria ambigua*). *Molecular Ecology* **19**, 4723–4737.

Garrick D., Siebentritt M. A., Alyward B., Bauer C. J. and Purkey A. (2009) Water markets and freshwater ecosystem services: policy reforms and implementation in the Columbia and Murray-Darling Basins. *Ecological Economics* **69**, 366–379.

Gehrke P. C., Brown P., Schiller C. B., Moffatt D. B. and Bruce A. M. (1995) River regulation and fish communities in the Murray-Darling River system, Australia. *Regulated Rivers: Research and Management* **11**, 363–375.

Gillanders B. M. and Kingsford M. J. (2002) Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology: An Annual Review* **40**, 233–309.

Gilligan D., Vey A. and Asmus M. (2009) Identifying drought refuges in the Wakool system and assessing status of fish populations and water quality before, during and after the provision of environmental, stock and domestic flows. New South Wales Department of Primary Industries –Fisheries Final Report Series No. 110.

Hames F., Townsend A., Ringwood G., Clunie P. and McPhail J. (2014) Effective engagement of the Native Fish Strategy is delivered by coordinated and contextual effort. *Ecological Management & Restoration* **15** (Suppl. 1), 13–27.

Hammer M., Bice C., Hall A. *et al.* (2013) Freshwater fish conservation in the face of critical water shortages in the southern Murray-Darling Basin, Australia. *Marine and Freshwater Research* **64**(9), 874–886.

Harris J. H. and Gehrke P. C. (1994) Modelling the relationship between streamflow and population recruitment to manage freshwater fisheries. *Agricultural Systems and Information Technology* **6**, 28–30.

Humphries P. (2005) Spawning time and early life history of Murray Cod, *Maccullochella peelii peelii* (Mitchell) in an Australian river. *Environmental Biology of Fishes* **72**, 393–407.

Humphries P. and King A. J. (2004) Drifting fish larvae in Murray-Darling Basin rivers: composition, spatial and temporal patterns and distance drifted. In *Downstream Movement of Fish in the Murray-Darling Basin. Statement, 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, Australia.

Humphries P., King A. J. and Koehn J. D. (1999) Fish, flows and floodplains: links between freshwater fishes and their environment in the Murray-Darling River system, Australia. *Environmental Biology of Fishes* **56**, 129–151.

Humphries P., Cook R. A., Richardson A. J. and Serafini L. G. (2006) Creating a disturbance: manipulating slackwaters in a lowland river. *River Research and Applications* **22**, 525–542.

Humphries P., Brown P., Douglas J. *et al.* (2008a) Flow-related patterns in abundance and composition of the fish fauna of a degraded Australian lowland river. *Freshwater Biology* **53**, 789–813.

Humphries P., Wilson G., Richardson A. J. and Ellison E. (2008b) *Impacts of Managed Flows on Fish Spawning and Recruitment*. Report prepared for the Murray-Darling Basin Commission. Charles Sturt University, Albury.

Humphries P., Richardson A., Wilson G. and Ellison T. (2012) River regulation and recruitment in a protracted-spawning riverine fish. *Ecological Applications* **23**, 208–225.

Jardine T. D., Pusey B. J., Hamilton S. K. *et al.* (2012) Fish mediate high food web connectivity in the lower reaches of a tropical floodplain river. *Oecologia*. **168**, 829–838.

Jones M. J. (2007) *Effects of Environmental Flow Allocations on the Lateral Movements of Native Fish in the Barmah–Millewa Forest*. Arthur Rylah Institute for Environmental Research, Heidelberg, Melbourne.

Jones M. J. and Stuart I. G. (2008) Regulated floodplains – a trap for unwary fish. *Fisheries Management and Ecology* **15**, 71–79.

Junk W. J., Bayley P. B. and Sparks R. E. (1989) The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* **106**, 110–127.

King A. J. (2004) Ontogenetic patterns of habitat use by fishes within the main channel of an Australian floodplain river. *Journal of Fish Biology* **65**, 1582–1603.

King A. J., Humphries P. and Lake P. S. (2003) Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics. *Canadian Journal of Fisheries and Aquatic Sciences* **60**, 773–786.

King A. J., Tonkin Z. and Mahoney J. (2007) Assessing the effectiveness of environmental flows on fish recruitment in Barmah-Millewa Forest. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, MDBC Project No. BMF 2004.09. Arthur Rylah Institute for Environmental Research, Heidelberg.

King A. J., Tonkin Z. and Mahoney J. (2009) Environmental flows enhance native fish spawning and recruitment in the Murray River, Australia. *Rivers Research and Applications* **25**, 1205–1218.

King A. J., Ward K. A., O'Connor P., Green D., Tonkin Z. and Mahoney J. (2010) Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. *Freshwater Biology* **55**, 17–31.

King A. J., Tonkin Z. and Lieschke J. (2012) Short-term effects of a prolonged blackwater event on aquatic fauna in the Murray River, Australia: considerations for future events. *Marine and Freshwater Research* **63**, 576–586.

Kingsford R. T. (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in australia. *Austral Ecology* **25**, 109–127.

Kingsford R. T. and Thomas R. F. (2004) Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee

River in arid Australia. *Environmental Management* **34**, 383–396.

Kingsford R. T., Walker K. F., Lester R. E. *et al.* (2011) A Ramsar wetland in crisis – the Coorong, lower lakes and the Murray mouth, Australia. *Marine and Freshwater Research* **62**, 255–265.

Koehn J. D. (2009) Multi-scale habitat selection by Murray Cod (*Maccullochella peelii peelii*) in two lowland rivers. *Journal of Fish Biology* **75**, 113–129.

Koehn J. D. (2013) Managing people, water, food and fish in the Murray-Darling Basin, south-eastern Australia. *Fisheries Management and Ecology*. doi:10.1111/fme.12035

Koehn J. D. and Harrington D. J. (2006) Conditions and timing of the spawning of Murray Cod (*Maccullochella peelii peelii*) and the endangered Trout Cod (*M. macquariensis*) in regulated and unregulated rivers. *Rivers Research and Applications* **22**, 327–343.

Koehn J. D. and Lintermans M. (2012) A strategy to rehabilitate fishes of the Murray-Darling Basin, south-eastern Australia. *Endangered Species Research* **16**, 165–181.

Koehn J. D., McKenzie J. A., O'Mahony D. J., Nicol S. J., O'Connor J. P. and O'Connor W. G. (2009) Movements of Murray Cod (*Maccullochella peelii peelii*) in a large Australian lowland river. *Ecology of Freshwater Fish* **18**, 594–602.

Koehn J. D., Hobday A. J., Pratchett M. S. and Gillanders B. M. (2011) Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research* **62**, 1148–1164.

Koehn J. D., Lintermans M. and Copeland C. (2014) Laying the foundations for fish recovery: The first 10 years of the Native Fish Strategy for the Murray-Darling Basin, Australia. *Ecological Management & Restoration* **15** (Suppl. 1), 3–12.

Leigh S. J. and Zampatti B. P. (2013) Movement and mortality of Murray Cod (*Maccullochella peelii*) during overbank flows in the lower River Murray, Australia. *Australian Journal of Zoology* **61**, 160–169.

Lester R. E., Webster I. T., Fairweather P. G. and Young W. J. (2011) Linking water-resource models to ecosystem-response models to guide water-resource planning – an example from the Murray-Darling Basin, Australia. *Marine and Freshwater Research* **62**, 279–289.

Lloyd L. and Walker K. F. (1986) Distribution and conservation status of small freshwater fish in the River Murray, South Australia. *Transactions of the Royal Society of South Australia* **110**, 49–57.

Lyon J. P. and O'Connor J. P. (2008) Smoke on the water: can riverine fish populations recover following a catastrophic fire-related sediment slug? *Austral Ecology* **33**, 794–806.

Lyon J., Stuart I., Ramsey D. and O'Mahoney J. (2010) The effect of water level on lateral movements of fish between river and off-channel habitats and implications for management. *Marine and Freshwater Research* **61**, 271–278.

Macdonald J. I., Tonkin Z. D., Ramsey D. S. L., Kaus A. K., King A. K. and Crook D. A. (2012) Do invasive eastern gambusia (*Gambusia holbrooki*) shape wetland fish assemblage structure in south-eastern Australia? *Marine and Freshwater Research* **63**, 659–671.

Mainstone C. P., Thomas R., Bean C. W. and Waterman T. (2012) The role of the UK conservation agencies in protecting river flows. *Fisheries Management & Ecology* **19**, 557–569.

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

Mallen-Cooper M. and Brand D. A. (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.

Mallen-Cooper M. and Stuart I. G. (2003) Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system. *River Research and Applications* **19**, 697–719.

Mallen-Cooper M., Koehn J., King A., Stuart I. and Zampatti B. (2008) Risk assessment of the proposed Chowilla regulator and managed floodplain inundations for fish. Report to Department of Water, Land and Biodiversity, South Australia. [Accessed 11 March 2014.] Available from URL: http://www.finterest.com.au/.

Mallen-Cooper M., Zampatti B., Hillman T. *et al.* (2011) Managing the Chowilla creek environmental regulator for fish species at risk. Report prepared for the South Australian Murray-Darling Basin Natural Resources Management Board. [Accessed 11 March 2014.] Available from URL: http://www.finterest.com.au/.

Malmqvist B. and Rundle S. (2002) Threats to the running water ecosystems of the world. *Environmental Conservation* **29**, 134–153.

McMahon T. A. and Finlayson B. L. (2003) Droughts and anti-droughts: the low flow hydrology of Australian rivers. *Freshwater Biology* **48**, 1147–1160.

MDBA (2010) *Guide to the Proposed Basin Plan: Overview*. 262 pp. Murray-Darling Basin Authority, Canberra. [Accessed 25 September 2012.] Available from URL: http://www.download.mdba.gov.au/Guide_to_the_Basin_Plan_Volume_1_web.pdf.

MDBA (2011) *Plain English Summary of the Proposed Basin Plan – Including Explanatory Notes*. 138 pp. Murray-Darling Basin Authority, Canberra. [Accessed 25 September 2012.] Available from URL: http://download.mdba.gov.au/proposed/plain_english_summary.pdf.

MDBC (2004) Native Fish Strategy for the Murray-Darling Basin 2003–2013. 64 pp. Murray-Darling Basin Commission, Canberra. [Accessed 25 September 2012.] Available from URL: http://www2.mdbc.gov.au/NFS.html.

MDBC (2006) *The Living Murray Foundation Report on the Significant Ecological Assets Targeted in the First Step Decision*. Murray-Darling Basin Commission, Canberra.

Milligan A. and Cottingham P. (2009) *Emerging Practice in Active Environmental Water Management in Australia: Report and Background Paper from Workshop Discussions among Practicing Environmental Water Managers*. eWater Cooperative Research Centre, University of Canberra and National Water Commission, Canberra, ACT.

Nilsson C. C., Reidy A., Dynesius M. and Revenga C. (2005) Fragmentation and flow regulation of the world's large river systems. *Science* **308**, 405–408.

Pittock J., Finlayson C. M. and Howitt J. A. (2013) Beguiling and risky: 'environmental works and measures' for wetland conservation under a changing climate. *Hydrobiologia*. **708**, 111–131.

Poff N. L., Allan J. D., Palmer M. A. *et al.* (2003) River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment* **1**, 298–306.

Rayner T. S., Jenkins K. M. and Kingsford R. T. (2009) Small environmental flows, drought and the role of refugia for freshwater fish in the Macquarie Marshes, arid Australia. *Ecohydrology* **2**, 440–453.

Reynolds L. F. (1983) Migration patterns of five fish species in the Murray-Darling River system. *Australian Journal of Marine and Freshwater Research* **34**, 857–871.

Richardson B. A. (1986) Evaluation of instream flow methodologies for freshwater fish in New South Wales. In: *Stream Protection: The Management of Rivers for Instream Uses* (ed I. C. Campbell), pp. 143–168. Water Studies Centre, Chisholm Institute Technology, Melbourne.

Rolls R. J. and Wilson G. G. (2010) Spatial and temporal patterns in fish assemblages following an artificially extended floodplain inundation event, Northern Murray-Darling Basin, Australia. *Environmental Management* **45**, 822–833.

Rolls R. J., Leigh C. and Sheldon F. (2012) Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshwater Science* **31**, 1163–1186.

Sherman B., Todd C. R., Koehn J. D. and Ryan T. (2007) Modelling the impact of cold water pollution and its potential mitigation on Murray Cod populations downstream of Hume Dam, Australia. *Rivers Research and Applications* **23**, 377–389.

Stuart I. G. and Jones M. (2006) Large, regulated forest floodplain is an ideal recruitment zone for non-native common carp (*Cyprinus carpio* L.). *Marine and Freshwater Research* **57**, 333–347.

Stuart I. G., Baumgartner L. and Zampatti B. P. (2008) Lock gates improve passage of small-bodied fish and crustaceans in a low gradient vertical-slot fishway. *Fisheries Management and Ecology* **15**, 241–248.

Swales S. and Harris J. H. (1995) The Expert Panel Assessment Method EPAM: a new tool for determining environmental flows in regulated rivers. In: *The Ecological Basis for River Management* (eds D. M. Harper and A. J. D. Ferguson), pp. 125–134. John Wiley & Sons, Chichester, UK.

Tockner K., Malard F. and Ward J. V. (2000) An extension of the flood pulse concept. *Hydrological Processes* **14**, 2861–2883.

Tonkin Z. D., King A. J., Robertson A. I. and Ramsey D. S. L. (2011) Early fish growth varies in response to components of the flow regime in a temperate floodplain river. *Freshwater Biology* **56**, 1769–1782.

Vilizzi L. (2012) Abundance trends in floodplain fish larvae: the role of annual flow characteristics in the absence of overbank flooding. *Fundamental and Applied Limnology* **181**, 215–227.

Vörösmarty C. J., McIntyre P. B., Gessner M. O. *et al.* (2010) Global threats to human water security and river biodiversity. *Nature* **467**, 555–561.

Walker K. F. (2006) Serial weirs, cumulative effects: the lower River Murray, Australia. In: *Ecology of Desert Rivers* (ed R. Kingsford), pp. 248–279. Cambridge University Press, Cambridge.

Walker K. F. and Thoms M. C. (1993) Environmental effects of flow regulation on the lower River Murray, Australia. *Regulated Rivers: Research and Management* **8**, 103–119.

Ward K. and Colloff M. (2010) Chapter 20: Ecosystem response modelling for the Barmah-Millewa Forest: the interface between science and management. In: *Ecosystem response Modelling in the Murray-Darling Basin* (eds N. Saintilan and I. Overton), pp. 345–357. CSIRO Publishing, Canberra.

Ward J. V. and Stanford J. A. (1995) Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers: Research and Management* **11**, 105–119.

Ye Q., Jones K. and Pierce B. E. (2000) *Murray Cod (Maccullochella peelii peelii), Fishery Assessment Report to PIRSA for Inland Waters Fishery Management Committee, South Australian Fisheries Assessment Series 2000/17*. SARDI Adelaide, Australia.

Zampatti B. P. and Leigh S. J. (2013a) Effects of flooding on recruitment and abundance of Golden Perch (*Macquaria ambigua ambigua*) in the lower River Murray. *Ecological Management and Restoration* **14**, 135–143.

Zampatti B. P. and Leigh S. J. (2013b) Within-channel flows promote spawning and recruitment of golden perch, *Macquaria ambigua ambigua* – implications for environmental flow management in the River Murray, Australia. *Marine and Freshwater Research*. **64**(7), 618–630.

Zampatti B. P., Leigh S. J. and Nicol J. M. (2011) Fish and aquatic macrophyte communities in the Chowilla Anabranch System, South Australia. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000719-1. SARDI Research Report Series No. 525.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Fish-related environmental flows in the Murray-Darling Basin between 1993 and 2012.

Table S2. Examples of the benefits, risks and limitations to Murray-Darling Basin fish of different environmental watering options and examples of EWAs.