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Adaptive management of an environmental watering event to enhance native fish spawning and recruitment

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SUMMARY

1. A common goal of many environmental flow regimes is to maintain and/or enhance the river's native fish community by increasing the occurrence of successful spawning and recruitment events. However, our understanding of the flow requirements of the early life history of fish is often limited, and hence predicting their response to specific managed flow events is difficult. To overcome this uncertainty requires the use of adaptive management principles in the design, implementation, monitoring and adjustment of environmental flow regimes.
2. The Barmah-Millewa Forest, a large river red gum forest on the Murray River floodplain, south-east Australia, contains a wide variety of ephemeral and permanent aquatic habitats suitable for fish. Flow regulation of the Murray River has significantly altered the natural flood regime of the Forest. In an attempt to alleviate some of the effects of river regulation, the Forest's water regime is highly managed using a variety of flow control structures and also receives targeted Environmental Water Allocations (EWA). In 2005, the largest environmental flow allocated to date in Australia was delivered at the Forest.
3. This study describes the adaptive management approach employed during the delivery of the 2005 EWA, which successfully achieved multiple ecological goals including enhanced native fish spawning and recruitment. Intensive monitoring of fish spawning and recruitment provided invaluable real-time and ongoing management input for optimising the delivery of environmental water to maximise ecological benefits at Barmah-Millewa Forest and other similar wetlands in the Murray-Darling Basin.
4. We discuss possible scenarios for the future application of environmental water and the need for environmental flow events and regimes to be conducted as rigorous, large-scale experiments within an adaptive management framework.

Keywords: Murray River, Barmah-Millewa Forest, floodplain river, regulated flows

Introduction

The need for a controlled water regime to provide for irrigation, human consumption, industry, flood control and hydroelectricity generation has led to the regulation of many of the world's rivers (Dynesius &

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Nilsson, 1994). The alteration of flow regimes by the construction and operation of dams has caused substantial impacts on the ecological health of rivers (Sparks, 1995; Stanford *et al*., 1996; Ward, Tockner & Schiemer, 1999; Bunn & Arthington, 2002). In flow altered rivers, the application of a more natural flow regime is thought to provide an opportunity for ecosystem recovery, for example through the enhancement of recruitment and growth processes (Stanford *et al*., 1996; Poff *et al*., 1997; Rood *et al*., 2003; Arthington *et al*., 2006). The management of 'environmental flows' for river restoration aims to mimic components of the river's natural flow variability, including the magnitude, frequency, timing, duration, rate of change and predictability of flow events (Arthington *et al*., 2006). However, water managers are often unable to return large volumes of water to the environment and therefore there is substantial pressure to use the available water wisely to maximise ecological benefits.

A common goal of many environmental flow regimes is the maintenance and enhancement of the native fish community. This strategy is based on the premise that aspects of the flow regime are linked to key components of the life history of many riverine fish, including pre-spawning condition and maturation, movement cues, spawning cues and behaviour, and larval and juvenile survival through the generation of food and availability of suitable habitats (e.g. Junk, Bayley & Sparks, 1989; Humphries, King & Koehn, 1999; Marchetti & Moyle, 2001; King, Humphries & Lake, 2003; Balcombe *et al*., 2006). Since the strength of recruitment, and therefore the future population, is mainly driven by the success of spawning events and the survival of young, understanding how the flow regime influences the early life history of fishes is critical to managing fish populations. Water managers need information on the specific components of a flow regime required to sustain these critical life history processes. For example, if successful spawning of a particular species is thought to be linked to flooding, when should it be provided? What magnitude, duration and shape of the flood peak should be designed in a managed flood pulse? Unfortunately, to date our knowledge of the flow requirements for most fish species is fairly poor, particularly for Australian species (Humphries *et al*., 1999; Bunn & Arthington, 2002; King *et al*., 2003; Pusey, Kennard & Arthington, 2004). To address these considerable and important information gaps, long-term manipulative experiments are needed where environmental water is applied, and the predicted ecological responses are monitored in a rigorous scientific manner (Poff *et al*., 2003; Schreiber *et al*., 2004). This experimental approach requires scientists and managers to employ adaptive management principles in the implementation and development of environmental flow regimes, with the overall aim of applying a flow regime based on current best knowledge, testing it by sound scientific monitoring, followed by a review and refinement of the flow regime and then implementing an adjusted flow regime as required (Poff *et al*., 2003; Richter *et al*., 2006). Although environmental flow management seems to be ideally suited to an adaptive management approach, the application of these principles has been extremely limited (Richter *et al*., 2006).

This study describes the adaptive and cooperative management arrangements employed during the delivery of a large Environmental Water Allocation (EWA) at the Barmah-Millewa (BM) Forest on the Murray River, south-east Australia in 2005/06 (Fig. 1). The watering event was designed to achieve multiple ecological outcomes for the Forest including enhanced native fish spawning and recruitment. We present the management context, the approach taken, the hypotheses tested and the major results for fish and other major floodplain taxa. We then discuss the options and limitations of possible future environmental watering scenarios at the Forest that may also achieve positive outcomes for fish as well as other ecological objectives. We end with special emphasis on the need for environmental watering events to be viewed as experiments, where a variety of flow scenarios can be trialled and intensively monitored, and the information gained from each 'experiment' incorporated into future water management strategies.

Background

The BM Forest is located on the Murray River upstream of the township of Echuca, in south-eastern Australia (Fig. 1). The Forest is recognised as a significant floodplain wetland and is listed as an internationally important wetland under the Ramsar convention. The river red gum (*Eucalyptus camaldulensis*, Dehnhardt) Forest is a 70 000 ha highly complex wetland system, with a range of aquatic habitats

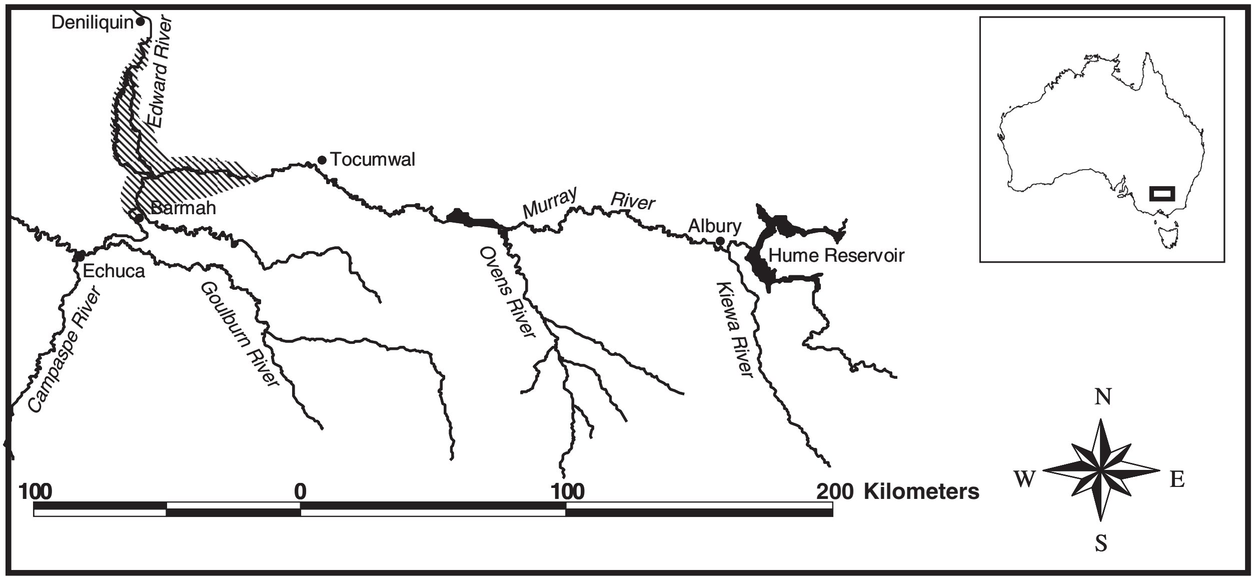

Fig. 1 Location of Barmah-Millewa Forest (hatched area) on the Murray River, south-east Australia.

present including rivers, permanent and ephemeral creeks, wetlands, swamps and the floodplain proper when inundated. Historically, the BM Forest region of the Murray River contained an abundant and diverse range of native fish, and fish were a major component of the diet for the local aboriginal community (King, 2005). Until around the 1930s, the area also supported the largest inland commercial fishery in Australia (see citations in King, 2005). The Forest still remains an important area for native fish although, since European settlement and regulation of the Murray River by dams and weirs, native fish have been substantially reduced in both abundance and diversity, and exotic species are common (King, 2005). Ten of the region's 18 native species are listed as threatened under State or Federal legislation, with a number of these species, such as Murray cod (*Maccullochella peelii peelii*, Mitchell), trout cod (*Maccullochella macquariensis*, Cuvier), silver perch (*Bidyanus bidyanus*, Mitchell), Murray rainbowfish (*Melanotaenia fluviatilis*, Castelnau) and southern pygmy perch (*Nannoperca australis*, Günther), known to have significant populations in the region. Several native fish species are also very popular for recreational fishing and a number of species retain important cultural values for the local aboriginal community.

The adverse effects of flow alteration in the decline in abundance and distribution of native Murray-Darling Basin (MDB) fishes, have been attributed to the removal of reproductive cues, barriers to movement, altered temperature regimes, reductions in aquatic vegetation and deeper pool habitats and reduced access to the floodplain (Cadwallader, 1978; Gehrke *et al.*, 1995; MDBC, 2004). While the tenets of the Flood Pulse Concept (Junk *et al.*, 1989), which highlights the importance of floodplain inundation for successful fish recruitment, have been extrapolated to Australian floodplain rivers (Harris & Gehrke, 1994; Schiller & Harris, 2001), there is little evidence linking flooding to enhanced spawning and/or recruitment of native MDB fishes (Humphries *et al.*, 1999; King *et al.*, 2003). Given this lack of understanding of the specific flow requirements of early life-history stages of native MDB fishes, predicting their potential responses to environmental flows at BM was difficult. This was identified as a major knowledge gap for management of the BM EWA (BMF, 2002), and a major project investigating the effects of various water management scenarios on fish spawning and recruitment within the Forest region commenced in 2003. This study intensively sampled eggs, larvae and juvenile fishes from September to February (the main breeding season for most species), over 5 years from 2003/04 to 2007/08. The first two seasons were hydrologically similar, with flooding occurring in winter/spring and summer flows confined largely within the river channel; whereas the third year (2005/06) encompassed 4 months of extensive floodplain inundation (enhanced by a managed EWA); and the last 2 years encompassed extreme drought conditions with many floodplain habitats drying and the Murray River experiencing record low flows.

Flow management at BM forest

Flow regulation of the Murray River has significantly altered the natural flooding and drying cycles of the Forest, and it now experiences a reduction in the frequency, duration and inundation area of winter–spring floods, altered timing of all floods and low flow periods, increased frequency of smaller summer floods and reduced annual variability in flood flows (MDBMC, 2001). In an attempt to alleviate some of the hydrological changes that threaten the ecological integrity of the BM Forest, the Forest's watering regime is highly managed by flow control structures and includes a targeted EWA. The specific allocation of up to 150 GL year^{-1} of environmental water, with carry-over rules to permit accrual over several years of up to 700 GL, allows for significant water management opportunities at the Forest (MDBMC, 2001). Use of the EWA is not required each year, and the allocation is often accumulated for a number of years and released in larger volumes, typically to extend the duration of natural flow events originating from the less regulated Kiewa and Ovens Rivers upstream (Fig. 1). By accumulating and releasing the allocation in this way, the EWA contributes a small, but significant component of the total volume of water required to inundate the floodplain; in effect it allows the restoration of some small to medium level floods that typically would have occurred naturally on a nearly annual basis (Ward, 2005). Floods of a larger magnitude will now only occur if the major upstream regulating structure, Hume Reservoir, is at or near capacity and spills.

The BM EWA has been released three times since its inception in 1993. In 1998, 97 GL was released from Hume Reservoir to extend the duration of a minor spring flood in the BM Forest after 22 months without floodplain connection. Despite a range of flora and fauna generally responding positively to the event (although no monitoring of fish responses occurred), the period of inundation and depth of the event were considered insufficient to achieve all of the desired ecological objectives (Maunsell McIntyre Pty Ltd, 1999). The second use of the EWA occurred in spring/summer 2000/01, with 341 GL released from Hume Reservoir to extend the duration of a large spring flood (Maunsell McIntyre Pty Ltd, 2001). The EWA supplemented a one in 5-year flood event for the Forest, and was released in a number of parcels over the season to reduce the rate of recession of major flood peaks and therefore prolong the duration of the inundation period. This management technique, known locally as 'filling holes' in the river, is aimed principally at slowing the flood recession rate to prevent breeding colonial waterbirds from abandoning their nests if the water in the floodplain wetlands subsides too rapidly (Ward, 2005). This use of the 2002/01 EWA resulted in a significant waterbird breeding event, with some species breeding in the Forest for the first time in 20 years (Leslie & Ward, 2002). While the event also had positive outcomes for vegetation and frogs (Maunsell McIntyre Pty Ltd, 2001), the responses of fish to this managed flood were not determined.

In 2004, the MDB Ministerial Council established 'The Living Murray' initiative, a long-term program of collective actions aimed at returning the Murray River system to the status of a 'healthy working river' (COAG, 2004) (http://www.thelivingmurray.mdbc.gov.au). A major feature component of this initiative is to recover a long-term average of up to 500 GL year^{-1} of water over a period of 5 years, aimed at improving environmental flows and to achieve defined ecological objectives at six icon sites along the River, including the BM Forest. While the aim of the initiative is to restore the broader ecological health of the River and its icon sites, improvements in the health of vegetation, birds and fish are seen as key ecological outcomes, and most restoration attention in the River is focused on these three indicators. The BM EWA predates, and is operated under different management and policy structures, than 'The Living Murray' initiative, and is therefore managed in a different manner than other environmental water within 'The Living Murray' initiative. However, any lessons learnt from uses of the BM EWA will assist in the future management of any 'Living Murray' water entitlements at BM and at other icon sites along the River.

Management of the 2005 BM EWA

The third use of the BM EWA was undertaken in 2005/06. At 513 GL, it surpassed in magnitude previous uses of the BM EWA, and resulted in the largest environmental water delivery undertaken to date in Australia. In the preceding dry years leading up to the delivery of the 2005 EWA, the allocation had been 'loaned' to the irrigation industry, and in May 2005 there was only a 10% chance that there would be enough inflows into the Hume Reservoir to allow payback of water to the river environment. However, by October 2005, better than average rainfall in the upper Murray catchment resulted in the full payback of the BM EWA, and therefore there was the potential that the EWA could be used that season. Natural flooding of the Forest occurred in August and September and it became apparent that floodplain inundation would cease in early to mid October if the EWA was not used. Within a week, a committee (comprising members from the pre-existing BM Technical Advisory Committee and the BM Coordination Committee) was formed to manage the watering event. This event-based Operations Committee consisted of technical experts from a number of disciplines with skills in river operation, Forest management, communication and relevant ecological expertise and senior Managers from the MDB Commission, local Catchment Management Authorities and State Government agencies. The Operations Committee initiated the approval process which enabled the release to be undertaken, and then developed a potential release hydrograph and operating and monitoring plans for the use of the EWA (see Fig. 2a). These plans were approved by higher level committees of senior managers within the relevant State Government agencies and the MDB Commission, and were signed off by appropriate State Ministers on 11th October 2005.

The 2005 EWA release was aimed at achieving multiple ecological objectives; including providing appropriate flood depth and duration to improve vegetation health, enhancing breeding opportunities and recruitment for native fish and frogs, improving wetland condition and sustaining any waterbird breeding events should they occur. Unlike previous uses of environmental water at BM Forest, the planned use of the 2005 EWA did not initially include colonial waterbird breeding, as there was doubt that a flood of sufficient size would occur to trigger a waterbird breeding event. Fortuitously, the provision of the 2005 EWA coincided with existing research programs on the recruitment and movement responses of fish to various water management scenarios, and with other 'flood event-only based' monitoring programs on vegetation condition, water quality and the breeding responses of frogs, colonial waterbirds and white-bellied sea-eagles (*Haliaeetus leucogaster*, Gmelin). It was therefore possible to capture highly relevant research data and explore the ecological consequences of the EWA for many ecosystem components and to input this information into better management in real-time and future management of other watering events.

To our knowledge, the incorporation of flow components into an environmental flow allocation that includes as a major objective enhancing native fish spawning and recruitment had not been previously undertaken in Australia. To achieve this, the Operations Committee initially planned to incorporate peaks in the hydrograph (varying discharge from 15 000 to 18 000 ML day^{-1}, rising 1000 ML day^{-1} and falling at 500 ML day^{-1}) during floodplain inundation, and to maintain floodplain inundation for 1–2 months. This flood regime was based largely on two hypotheses: that golden perch (*Macquaria ambigua*, Richardson) and silver perch require rising flows and/or floods to trigger spawning (Lake, 1967; Harris & Gehrke, 1994; Mallen-Cooper & Stuart, 2003); and that floodplain inundation should provide conditions suitable for the successful rearing of larvae and juveniles, and therefore enhance subsequent recruitment of these and other fish species (Junk *et al*., 1989; Harris & Gehrke, 1994). Whilst at that time there was little empirical evidence supporting either of these hypotheses for MDB fishes (Humphries *et al*., 1999; King *et al*., 2003), these objectives were incorporated into the initial management of the 2005 EWA essentially as an experiment. This decision was reached because the suggested flow components (discharge volume, timing of peaks, rates of rise and fall and duration of floodplain inundation) were expected to complement other ecological outcomes of the flooding event. In addition, both hypotheses could be tested as part of an existing fish recruitment research project which had already collected two seasons of data (during a period when no spring/summer flooding occurred) that would be suitable for comparison with the outcomes of the EWA flooding experiment.

The bulk of the EWA release occurred from mid-October until mid-December 2005, providing medium level flooding to approximately 57% of the BM

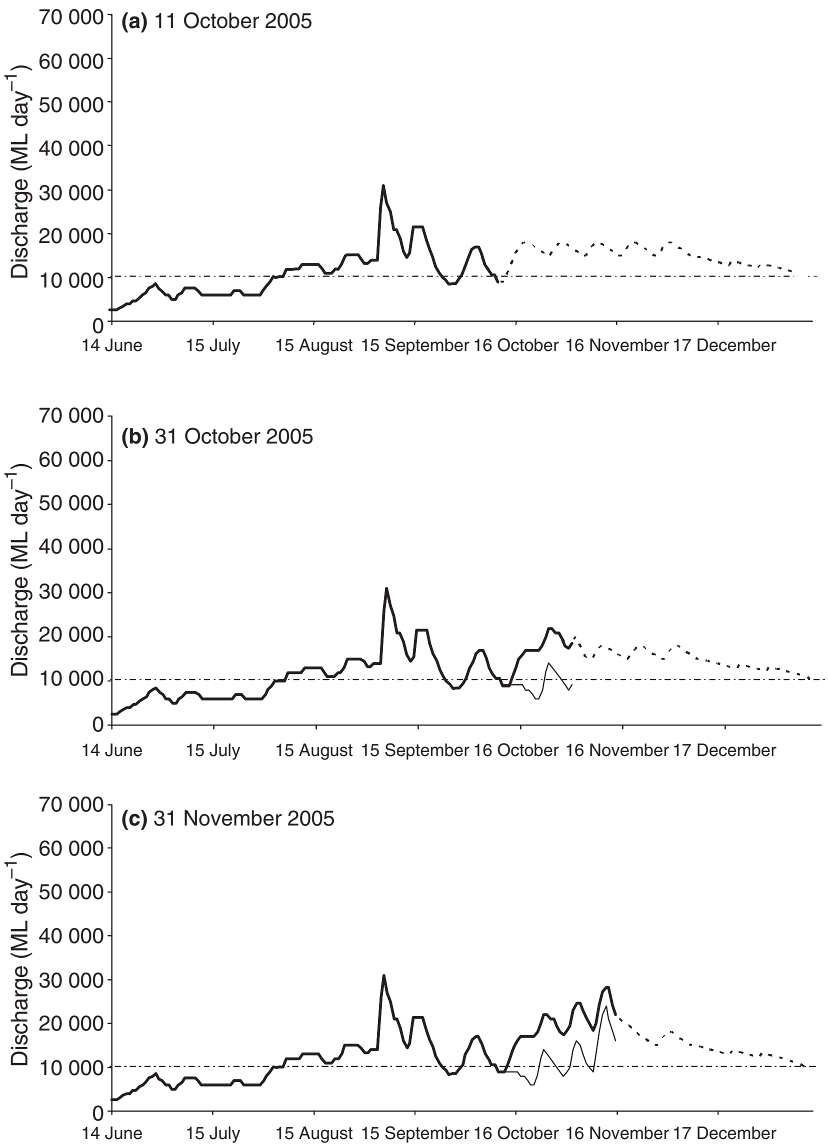

Fig. 2 Actual discharge (heavy solid line), planned flow regime (dashed line) and simulated flow without use of Barmah-Millewa Environmental Water Allocation (light solid line) in the Murray River downstream of Yarrawonga weir, at three critical management decision points in the 2005 season. All flows were measured or simulated downstream of Yarrawonga on Murray River (upstream of Barmah-Millewa). Floodplain inundation height (10 200 ML day^{-1}) also shown. Simulated natural flow refers to results of modelled flows based on tributary inputs and no upstream river regulation.

floodplain. The flow through the Forest was then progressively tapered off using regulated flows, managed through a number of the 51 Forest regulators (flow control structures) until the 13th March 2006, principally to provide for the successful fledging of over 50 000 colonial waterbirds. Interestingly, while the EWA significantly enhanced the depth and duration of floodplain inundation in the Forest (note difference between recorded and simulated discharge downstream of Yarrawonga in Fig. 3), under modelled 'natural' conditions (i.e. the absence of dams and extractions) continuous flooding would have occurred for a longer duration (a total of 5 months) and higher magnitude (Fig. 3).

The real-time management and delivery of the EWA was crucial, and was managed by a multidisciplinary Operations Committee (as described above). The committee was convened weekly by telephone conferences during the event, enabling decisions to be made in direct response to the results of existing ongoing monitoring, and allowing for management actions to be planned for the week/s ahead. For example, by the end of October 2005, 190 GL of the EWA had already been released and consideration was given to ceasing the EWA release. However, the peak in natural flood flows in late October, derived from substantial rainfall in upstream tributaries, had triggered significant spawning of silver perch and

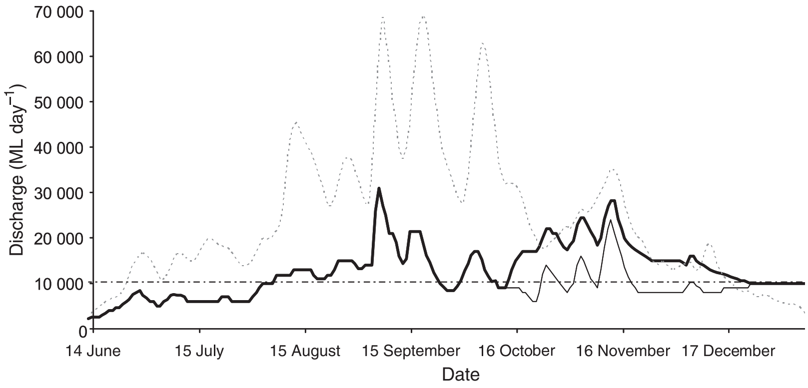

Fig. 3 Actual mean daily discharge (heavy solid line); simulated mean daily discharge without use of Environmental Water Allocation (EWA) (thin solid line); simulated natural flows (dotted line) during the 2005 use of the Barmah-Millewa EWA. All flows were measured or simulated downstream of Yarrawonga on Murray River (upstream of Barmah-Millewa). Simulated natural flow refers to results of modelled flows based on tributary inputs and no upstream river regulation. Floodplain inundation height (10 200 ML day^{-1}) also shown.

golden perch (King, Tonkin & Mahoney, in press). This real-time information contributed to the Committee's decision to continue with the EWA release using the planned strategy, with the objective of triggering further spawning events and also aiming to sustain flooding of a sufficient duration to provide suitable larval and juvenile fish rearing conditions (Fig. 2b). Rainfall in the upstream tributaries throughout early November 2005 provided further natural flow peaks (hence the planned managed flow variability was provided naturally) and triggered the breeding of a number of colonial waterbirds. The bird species involved are known to be sensitive to rapid water drawdown, hence the rate of recession of the declining flood hydrograph was now important to manage (Fig. 2c). We believe that this type of real-time, adaptive management of the EWA release was critical in ensuring that the ecological success of the event was maximised and included a number of ecosystem attributes.

Results

General ecological outcomes of the 2005 BM EWA

The 2005 managed flood event and use of the BM EWA resulted in significant ecological outcomes for the Forest and the associated river ecosystem, including: enhanced growth and health of significant native vegetation species; a highly significant waterbird breeding event for the Forest, with more than 52 000 colonial waterbirds from a number of different species successfully breeding (including nankeen night heron (*Nycticorax caledonicus* Gmelin), great egret (*Ardea alba* L.), intermediate egret (*Ardea intermedia* Wagler), little egret (*Ardea garzetta* L.), sacred ibis (*Threskiornis molucca* Latham), straw-necked ibis (*Threskiornis spinicollis* Jameson) and royal spoonbills (*Platalea regia* Gould)); successful breeding of a number of frog species [including Peron's tree frog (*Litoria peroni* Tschudi), Eastern banjo frog (*Limnodynastes dumerili* Peters), barking marsh frog (*Limnodynastes fletcheri* Boulenger), spotted marsh frog (*Limnodynastes tasmaniensis* Günther), plain's froglet (*Ranidella parinsignifera* Main) and the common froglet (*Ranidella signifera* Girard)]; successful breeding of white-bellied sea eagles (MDBC, 2006; O'Connor, Ward & King, 2007); and a significant exchange of organic material and soluble nutrients between the floodplain and main channel that stimulated secondary production in both environments (H. Gigney, Murray-Darling Freshwater Research Centre, unpubl. data).

Fish response to the 2005 BM EWA

Intensive monitoring of fish spawning and recruitment demonstrated that the flood event achieved several of the hypothesised ecological outcomes outlined above (Table 1), including enhancement of spawning and/or recruitment of several significant native species: golden perch, silver perch, Murray cod, trout cod and southern pygmy perch (King, Tonkin & Mahoney, 2007; King *et al.*, in press; Tonkin, King & Mahoney, 2008). Golden and silver perch increased their spawning activity (measured as the number of drifting eggs collected using drift nets set overnight at fortnightly intervals over their spawning period) during the 2005 flood relative to the other monitoring years where extensive spring–summer flooding did not occur (King *et al.*, in press). While Murray cod and trout cod did not increase spawning

Table 1 Fish species collected in Barmah-Millewa Forest on the Murray River from 2003/04 to 2005/06, and their response to the 2005/06 flood year that included an environmental water allocation, as compared to the other two previous years where little flooding occurred during the spawning season

Common name	Scientific name	Summary of known responses to 2005/06 flood year	Comment
Native species			
Golden perch	*Macquaria ambigua*	Increased spawning activity	Measured as number of drifting eggs/water volume in Murray River Not conclusively known if spawning cue is flow rise or floodplain inundation Recruitment success not known (see King *et al*., in press)
Silver perch	*Bidyanus bidyanus*	Increased spawning activity	Measured as number of drifting eggs/water volume in Murray River Not conclusively known if spawning cue is flow rise or floodplain inundation Recruitment success not known (see King *et al*., in press)
Murray cod	*Maccullochella peelii peelii*	Increased abundance of YOY recruits	Measured as number of YOY fish captured in standardised boat electrofishing in the Murray River at the end of spawning season Limited data across year's available; result should be treated with caution (see King *et al*., in press). High abundance of YOY also recorded in very low flow year (2007/08) (A.J. King, unpubl. data)
Trout cod	*Maccullochella macquariensis*	Increased abundance of YOY recruits	Measured as number of YOY fish captured in standardised boat electrofishing in the Murray River at the end of spawning season Limited data across year's available; result should be treated with caution (see King *et al*., in press). High abundance of YOY also recorded in very low flow year (2007/08) (A.J. King, unpubl. data)
Southern pygmy perch	*Nannoperca australis*	Increased abundance of YOY recruits Increased dispersal	Recruitment measured as number of juveniles captured in all habitat types using methods targeted at sampling small-bodied fish Dispersal measured as occurrence in habitat types sampled across the floodplain Low total number of individuals collected, result should be treated with caution (see King *et al*., 2007; Tonkin *et al*., 2008)
Australian smelt	*Retropinna semoni*	No change in abundance of larvae or juveniles No change in time of spawning	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al*., 2007)
Carp gudgeons	*Hypseleotris* spp.	No change in abundance of larvae or juveniles No change in time of spawning	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al*., 2007)
Flat-headed gudgeon	*Philypnodon grandiceps*	No change in abundance of larvae or juveniles. Spawned earlier than in previous years, during flood onset	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al*., 2007)
Unspecked hardyhead	*Craterocephalus stercusmuscarum fulvus*	No change in abundance of larvae or juveniles. Spawned earlier than in previous years, at flood onset	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al*., 2007)

Table 1 (*Continued*)

Common name	Scientific name	Summary of known responses to 2005/06 flood year	Comment
Murray-Darling rainbowfish	*Melanotaenia fluviatilis*	No change in abundance of larvae or juveniles No change in time of spawning	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al.*, 2007)
Exotic species			
Carp	*Cyprinus carpio*	Increased abundance of larvae and YOY recruits. Spawned earlier than in previous years, at flood onset	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Measured as number of YOY fish captured in standardised boat electrofishing in the Murray River at the end of spawning season. Limited data across year's available; result should be treated with caution. High abundance of YOY also recorded in very low flow year (2007/08) (A.J. King, unpubl. data) Spawning measured as presence of newly hatched larvae (see King *et al.*, 2007)
Goldfish	*Carasius auratus*	Increased abundance of YOY recruits. Spawned earlier than in previous years, at flood onset	Measured as number of YOY fish captured in standardised boat electrofishing in the Murray River at the end of spawning season Limited data across year's available; result should be treated with caution Spawning measured as presence of newly hatched larvae (see King *et al.*, 2007)
Redfin perch	*Perca fluviatilis*	No change in abundance of larvae or juveniles No change in time of spawning	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al.*, 2007)
Eastern gambusia	*Gambusia holbrooki*	No change in abundance of larvae or juveniles. Spawned later than previous years, after flood had receded	Measured as number of larvae or juveniles captured in all habitat types using methods targeted at sampling small-bodied fish. Spawning measured as presence of newly hatched larvae (see King *et al.*, 2007)
Oriental weatherloach	*Misgurnus anguillicaudatus*	Increased recruitment	Measured as number of juveniles captured in all habitat types using methods targeted at sampling small-bodied fish (see King *et al.*, 2007)

Table is based on known responses from analyses conducted to date on only 3 years of data, and results should therefore be treated with caution. Further analysis to be conducted.
YOY, young-of-year.

activity (measured as the number of drifting larvae collected using drift nets set overnight at fortnightly intervals over their spawning period), higher abundances of young-of-year fish were collected in the river using standardised boat electrofishing after the 2005 flood season (King *et al.*, in press). This suggests that flooding may enhance the survival of larvae and juveniles of these two species, however, subsequent monitoring has also shown that high abundances of young-of-year fish can also occur during extremely low river flow conditions (A.J. King, unpubl. data), this result therefore requires further validation and exploration. Although only low numbers of southern pygmy perch were collected throughout the 5-year study, the highest abundance of juveniles (and total individuals) and the highest number of sites containing this species were recorded in the 2005/06 flood season, suggesting that flooding may be important for enhancing recruitment and dispersal of this species (Tonkin *et al.*, 2008).

Counter to the generally accepted model of the importance of floods for fish recruitment in lowland rivers (Junk *et al.*, 1989; Harris & Gehrke, 1994; Schiller & Harris, 2001), there was no statistically significant increase in the total abundance of larvae and juveniles of most native species [especially the smaller-bodied species, such as Australian smelt (*Retropinna semoni* Weber) and carp gudgeons (*Hypseleotris* spp.)] as a result of the 2005 flood compared to the previous year's records (King *et al.*, 2007), however further analysis is currently been conducted to examine this relationship more fully. Other studies have also reported no increase in the abundance of juveniles of some species as a result of flooding (King *et al.*, 2003; Balcombe *et al.*, 2006; Zeug & Winemiller, 2007, 2008). The lack of response of some species to the 2005 BM EWA may in part be attributable to the EWA not mimicking the natural conditions that would have occurred without river regulation, particularly the duration and magnitude of floodplain inundation. Although the influence of this factor is impossible to tease out in this instance, future monitoring of similarly timed flood events of greater duration and/or magnitude may aid in elucidating the influence of various flow components on fish spawning and recruitment. Whilst most native fish in the BM Forest were found not to require a flow rise or floodplain inundation to stimulate spawning, many species altered the timing of their spawning period in the 2005 flood season (see Table 1) (King *et al.*, 2007). For example, flathead gudgeon (*Philypnodon grandiceps*, Krefft), unspecked hardyhead (*Craterocephalus stercusmuscarum fulvus,* Ivantsoff), carp (*Cyprinus carpio*, L.) and goldfish (*Carassius auratus*, L.) spawned earlier during the flood event than previous years, while eastern gambusia (*Gambusia holbrooki*, Girard) produced offspring later than the previous years, when flood waters had receded. King *et al.* (2003) also reported the delayed occurrence of gambusia larvae in floodplain wetlands after flooding had ceased. Additionally, many species were able to use floodplain wetland and creek habitats when they contained water to successfully spawn and recruit irrespective of the flooding conditions that occurred during the season (King *et al.*, 2007). Thus, although flooding was not essential as a spawning stimulus for many fish species, it did play an integral role in maintaining the diversity of habitat types available across the floodplain and provided an important opportunity for dispersal of fish between otherwise isolated habitats and populations, particularly for wetland specialists such as the threatened species, southern pygmy perch (King *et al.*, 2007; Tonkin *et al.*, 2008).

Undesirable outcomes of the 2005 BM EWA

The 2005 flooding event resulted in substantial benefits for the Forest and River ecosystem, however, it also resulted in a number of undesirable outcomes; such as increased spawning and recruitment success, and improved dispersal of exotic fish such as carp, goldfish and oriental weatherloach (*Misgurnus anguillicaudatus*, Cantor) (Macdonald & Crook, 2006; King *et al.*, 2007) and the trapping of large numbers of native fish in isolated pools immediately downstream of major regulators (Jones & Stuart, 2008). The 2005 flooding event also aided the rapid spread throughout the Forest of an exotic waterweed, arrowhead (*Sagittaria graminea*, Michaux) (K. Ward, pers. obs.). Prolonged flooding at the Forest can also result in 'blackwater' moving from the inundated floodplain Forest into the river channel. Blackwater is water extremely low in dissolved oxygen, but high in dissolved organic matter, and is a natural phenomenon of floodplain river processes (Howitt *et al.*, 2007). Whilst not an issue during the 2005 flood event (H. Gigney, Murray-Darling Freshwater Research Centre, unpubl. data), previous blackwater events have resulted in fish in the Murray River avoiding the Forest region as well as large numbers of Murray crayfish (*Eustacus armatus*, Von Martens) moving out of the water, making them vulnerable to desiccation and predation (McKinnon, 1997; Maunsell McIntyre Pty Ltd, 2001).

Discussion

One of the initial aims of the BM EWA was to provide reasonable flooding of the forest at least every 5 years (MDBMC, 2001). This rule was included on the basis of hydrological modelling that indicated there could be periods of up to 8 years between floods, assuming the continuance of the current levels of irrigation development and replication of the previous worst drought on record. This 8-year 'drought' in the Forest would not occur under natural conditions and was seen as too long to maintain a healthy forest ecosystem and to ensure regular waterbird breeding events. Spring 2005 marked the 5th year since the previous significant spring flooding of the BM Forest (Spring 2000). As such, the 5th year flooding rule was triggered and was one of the driving factors in the decision to release the EWA. At the time, the decision to release over 500 GL of water from storage during a significant drought period was a very difficult and contentious decision for senior managers and politicians, as some of the Murray-Darling River system was already under declared drought conditions and inflows into the storages that year were only average. In retrospect this decision was entirely justified given the significant ecological outcomes that occurred and the fact that the drought has continued and worsened (it is now in its 10th year). If the 2005 EWA release had not occurred, then the BM Forest and many other wetlands along the River Murray that also benefited from release of the EWA (MDBC, 2006), would likely be significantly more impacted than they are today and may well have been damaged irreversibly.

The results from this one managed flood event demonstrate the complexity and diversity of potential responses within a fish community to flooding. Indeed, different outcomes would be likely under different flow scenarios (King *et al.*, 2003, in press). For example, flooding outside of the normal spring–summer spawning period for most species would be unlikely to trigger any spawning response, but would provide water into wetlands for maintenance of fish habitat along with other potential benefits to the river ecosystem. The response to more subtle alterations in flooding patterns is likely to be more complex and more difficult to predict. For example, whilst a flood of much greater magnitude (Fig. 4a) would inundate more of the floodplain and therefore water more vegetation and wetlands in the Forest, would this larger flood result in an equivalent amplification in the number of successful fish recruits? Is the duration of the flow peak important? Would water delivered over a short period of time as a flood peak (Fig. 4b) provide the same ecological outcomes? The spawning of golden and silver perch may also be triggered by rises and falls in the hydrograph within the main channel, that is, without floodplain inundation occurring (Mallen-Cooper & Stuart, 2003; King *et al.*, 2007). Therefore, would a large spawning event for these species be triggered if the EWA was used to provide either several small inundation events (Fig. 4c) or several within channel flow rises (Fig. 4d)? Finally, what rate of rise and/or fall in the hydrograph is critical to trigger a spawning event for these species? Whilst it is important to manipulate flows and understand how fish respond to individual flow components, it must also be remembered that the diversity of life strategies within a fish community is likely to result in a range of different flow conditions being required (Humphries *et al.*, 1999; King *et al.*, 2003; Welcomme *et al.*, 2006), possibly not all in the same year or sequences of years. Indeed, limited understanding of the diversity of environmental conditions required by fish and other key taxonomic groups (e.g. waterbirds and vegetation) across all life history stages may result in the over-simplistic design and management of EWA in complex floodplain river systems.

The range of possible positive and negative ecological outcomes continue to be carefully considered and balanced by a range of relevant experts before any planned changes to water management occur at BM. We believe that these ongoing discussions have an important role in the management of a site of high conservation significance. Given the significant ecosystem benefits that can be achieved by the careful management and use of environmental flows, the risk of any negative consequences should not be considered as reasons to cease environmental water releases.

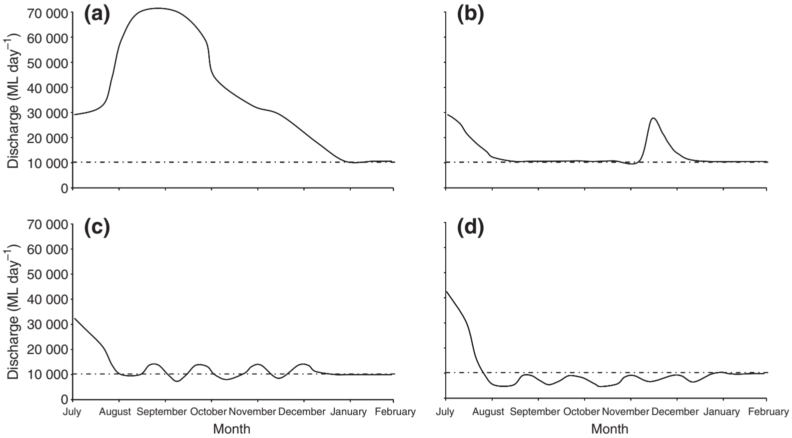

Fig. 4 Potential flow scenarios for Barmah-Millewa Forest that may enhance native fish spawning and recruitment. (a) Greater flood magnitude with longer duration, (b) small to medium level flood of short duration that may be supplied purely by EWA, (c) a series of small rises above floodplain inundation height to periodically inundate floodplain and (d) small spring–summer flow rises that occur within the banks of the main channel after winter flooding event. Floodplain inundation height (10 200 ML day^{-1}) also shown.

Rather, environmental flows need to be seen as an important, but only one, aspect of a suite of potential restoration activities (such as pest species management, improvement of fish passage and habitat restoration) that may also be needed to ensure improvements in the ecological health of a river system (Baron *et al.*, 2002; Bunn & Arthington, 2002; MDBC, 2004). Thorough monitoring of any potential negative effects of the EWA is also vital in understanding the variables which control them, and the new knowledge gained can result in subtle changes to the way future flow regimes are implemented so as to reduce negative impacts. For example, Jones & Stuart (2008) suggest that lowering flows in the Murray River while regulator gates are open may allow native fish to receive the cue of falling water levels, and thus allow them to escape the floodplain before the regulator gates are closed and fish are trapped in isolated pools behind the regulator. Flows may also be manipulated to trigger carp spawning by inundating floodplains and then rapidly reducing the water level to desiccate their eggs and larvae (Shields, 1957). Both of these proposed alterations to future managed floods in BM have not as yet been tested, and need to be considered in the context of their potential impact upon other components of the river ecosystem, all of which should be monitored and reviewed within an adaptive management framework (Cottingham *et al.*, 2005).

Conclusions

Water managers and stakeholders are now demanding from scientists more than just a strong conceptual understanding of the likely ecological responses of river biota to managed flows (Poff *et al.*, 2003; Arthington *et al.*, 2006). The perceived high cost of returning water to the environment is such that its use has to be carefully justified and tangible ecological benefits need to be demonstrated to all stakeholders. However, the complexity of potential responses by fish alone (without considering other aspects of river ecosystems), our current low level understanding about the relationships between fish and flow patterns, and the diversity of potential managed flows, all highlight the difficulty of predicting ecological outcomes in response to a particular managed flow event or flow regime (Welcomme *et al.*, 2006). To advance our understanding and improve management of future watering events at BM and in other river systems, the use of environmental flows in some catchments needs to be treated as large-scale manipulative experiments, where new flow regime scenarios are tested, rigorously monitored and reviewed using adaptive management involving a multidisciplinary team of scientists and managers (Arthington & Pusey, 2003; Poff *et al.*, 2003; Cottingham *et al.*, 2005; Arthington *et al.*, 2006; Richter *et al.*, 2006).

The traditional BACI (before-after-control-impact) design for monitoring impacts is often not possible for the assessment of environmental flows in large rivers, and it is therefore critical that longer-term monitoring at a specific location is undertaken to strengthen the inference that the environmental flow actually caused the predicted ecological response (Cottingham *et al.*, 2005). This type of manipulative, long-term restoration experiment obviously requires a strong commitment from management agencies to secure funding and resources. Monitoring should be targeted at demonstrating causal links between the responses of individual taxa to specific flow events and comparing these responses during flow and non-flow years. For example, as was demonstrated at BM, monitoring the spawning and subsequent recruitment response of fish to an actively managed EWA directly linked several response variables from the fish community to a specific flow event. This approach allows for scientifically defensible and credible improvement in our understanding of the flow requirements of target biota (Cottingham *et al*., 2005), and also allows for the confident development and exploration of predictive models. Simply monitoring the composition and relative abundance of the overall fish community on an annual basis, which is often implemented in basic condition assessment monitoring, does not allow for this type of causally linked information to be gathered. Richter *et al.* (2006) suggested that the selection of suitable indicators is of great importance, and that these indicators should be sufficiently responsive to flow management to enable evaluation of the success of the programme on relatively short-time frames. This type of hypothesis-driven, causally-linked monitoring should be viewed and conducted quite separately to surveillance monitoring, which is more concerned with assessing overall shifts in ecosystem condition or particular ecosystem variables, rather than establishing which factors may have caused any observed change (Bunn & Arthington, 2002; Downes *et al*., 2002; Cottingham *et al*., 2005).

If the science and management of environmental flows is to advance, scientists and managers need to work in a cooperative manner within interdisciplinary teams to assess various options and gauge their scientific uncertainty, and then generate sound, hypothesis-based, long-term monitoring programs focussed on key testable and responsive attributes and use the resultant information to improve future decision making (Poff *et al*., 2003). Unfortunately, the unpredictable nature of rainfall-runoff patterns in many regions and hence many river flow regimes can often create situations where the final flow regime achieved does not resemble the planned environmental flow regime. Hence, discussions with scientists and managers about the development of revised objectives, modified scientific monitoring designs and careful assessment of ongoing risks during the delivery of managed flow events are critical. We believe that the success of the case study described here was largely due to the transparent and cooperative approach of managers, scientists and various stakeholders; reinforced by evidence of beneficial outcomes for fish and other biota reported in real-time from targeted monitoring. The acknowledged scientific uncertainty identified at the outset of the EWA led to additional research and monitoring of key ecosystem indicators during the flood event that provided not only vital new knowledge to input into the real-time management of the watering event, but also provided valuable information and validation of the importance of environmental flows for the river ecosystem, and for stakeholders and the public.

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