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Australia's Murray–Darling Basin: freshwater ecosystem conservation options in an era of climate change

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Abstract. River flows in the Murray–Darling Basin, as in many regions in the world, are vulnerable to climate change, anticipated to exacerbate current, substantial losses of freshwater biodiversity. Additional declines in water quantity and quality will have an adverse impact on existing freshwater ecosystems. We critique current river-management programs, including the proposed 2011 Basin Plan for Australia's Murray–Darling Basin, focusing primarily on implementing environmental flows. River management programs generally ignore other important conservation and adaptation measures, such as strategically located freshwater-protected areas. Whereas most river-basin restoration techniques help build resilience of freshwater ecosystems to climate change impacts, different measures to enhance resilience and reoperate water infrastructure are also required, depending on the degree of disturbance of particular rivers on a spectrum from free-flowing to highly regulated. A crucial step is the conservation of free-flowing river ecosystems where maintenance of ecological processes enhances their capacity to resist climate change impacts, and where adaptation may be maximised. Systematic alteration of the operation of existing water infrastructure may also counter major climate impacts on regulated rivers.

Additional keywords: biodiversity, environmental flows, free-flowing, infrastructure, regulated, rivers, water, wetlands.

Introduction

The scenario facing Australia's Murray–Darling Basin (MDB) under projected climate change is bleak, with predicted increases in temperatures and evaporation, and less rainfall and reduced runoff to the rivers and wetlands being likely, especially in the southern MDB (CSIRO 2008; Dunlop and Brown 2008). We outline how a changing climate, coupled with the impacts of existing land and water uses, could further significantly change freshwater ecosystems in the MDB, unless conservation options are identified and successfully translated into on-ground outcomes. We then propose solutions. Lessons in managing the MDB may also have relevance for other geographically similar mid-latitude and dry tropics regions at risk of reduced runoff, such as the Mediterranean Basin, south-western USA, southern Africa and north-eastern Brazil (Bates *et al.* 2008; Powell 2008).

The MDB (1 061 500 km^2; Fig. 1) contains the longest river system in Australia. The high-rainfall alpine districts in the east account for 5% of the area and yet contribute over 50% of the runoff (CSIRO 2008). Irrigated land covers only 2% of the area, yet uses 90% of diverted waters to produce 70% of Australia's irrigated agricultural output, valued at AU$7 billion per year (ABS *et al.* 2009). With increasing concern over the state of the river and its wetlands, there are major questions about the sustainability of irrigation and the environment (Connell 2007). The MDB has high ecological values, with diverse species and ecosystems, nearly 5.7 million hectares of wetlands (Kingsford *et al.* 2004*a*), and 16 wetlands listed as internationally important under the Ramsar Convention on Wetlands (Fig. 1; DEWHA 2009).

We briefly review the changes to flow regimes, status of the cumulative effects of anthropogenic impacts, and expected impacts of climate change on freshwater biodiversity. Then, government programs to reallocate water for the environment are critically assessed. Finally, we discuss the broad range of options available to improve the conservation of the freshwater biodiversity within the context of climate change.

Hydrology and climate change

Rainfall across the MDB is temporally and spatially extremely variable, averaging 457 mm annually (1895–2006) (Chiew *et al.* 2008), with more in the south-east (mean annual >1500 mm) and eastern perimeter, and less in the west (<300 mm). In the north of the MDB, most rainfall occurs in summer, whereas the south receives most in winter. Evaporation is four times higher than rainfall. Only 6% of the rainfall is transformed into runoff to recharge the groundwater and flow into the streams (Chiew *et al.* 2008).

Southern Australia may be particularly vulnerable to climate change as global warming increasingly draws rain-bearing cold-pressure systems south over the Southern Ocean from

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Fig. 1. Location of the Murray–Darling Basin, Australia, showing Ramsar wetland sites, The Living Murray icon sites, and other places mentioned in the text.

autumn to spring. Average rainfall from October 1996 to May 2009 was the lowest within the instrumental period (Timbal 2009), leading to the loss of large quantities of water from the MDB's surface, soils and aquifers (Leblanc *et al.* 2009). Increased evapotranspiration as a result of increased air temperatures, more interception structures and land use have dramatically reduced runoff (van Dijk *et al.* 2006; Timbal and Jones 2008; MDBA 2009*a*). In the MDB, a 15% reduction of inflows has been observed for a 1°C rise in average temperature; a 2°C temperature rise by 2060 could result in a 55% reduction in inflows from reduced precipitation and increased evapotranspiration (Cai and Cowan 2008).

In 1980, there was warning that parts of the MDB may suffer reduced precipitation due to climate change (Pittock 1980), which was quantified from 1997 (Schreider *et al.* 1997), including at the sub-basin scale (Jones and Page 2001). A range of climate scenarios on impacts on MDB water yields for 2030 have now been assessed, ranging from similar or higher levels than the historical average impacts in the northern Darling River tributary catchments through to substantial declines in the southern MDB (CSIRO 2008). The implications of these changes in climate on water quantity and quality, and on the biodiversity would be significant.

Management interventions and environmental impacts

There was considerable investment in the Basin during the 20th century for irrigation, including to access and store water to mediate the impact of droughts and floods (Connell 2007). A cascade of weirs was constructed on the River Murray to promote river transport and then state governments invested in irrigation schemes to settle soldiers returning from the two world wars. Grand engineering schemes regulated the flow of the major rivers and transferred water across large distances for irrigation, most prominently the Snowy Mountains Scheme that diverts water from the Snowy River into the MDB to generate electricity and expand irrigated agriculture (Ghassemi and White 2007).

The period up to the 1990s was marked by increasing water withdrawals for irrigation and continuing reductions in the ecological health of the river system, including the decline of river fisheries, threats to the survival of many species and increasing salinity (Walker and Thoms 1993; Faragher and Harris 1994; Jolly *et al.* 2001; Goss 2003; Walker 2006). In 1991, a toxic cyanobacterial bloom that extended for 1000 km along the Darling River (Bowling and Baker 1996) was the clearest indicator that the health of the river system was reaching a crisis. In response, Australian governments placed a cap on surface water-extraction rights from the Murray–Darling at 1993–1994 levels, and programs commenced to ameliorate some of the problems, including interventions to reduce salinity levels, cyanobacterial blooms, restore native fish populations and provide environmental flows. However, these interventions failed to substantially slow the decline of ecosystems in the MDB (Chartres and Williams 2006; Connell 2007). With this background, we provide a summary of the key anthropocentric impacts and additional impacts anticipated from climate change on changes to water quantity and quality, and impacts on biodiversity.

Changes to water volumes

Most of the rivers in the MDB are over-allocated, shown by comparing the current end of system flow to natural flows (CSIRO 2008). Modelling of natural flow conditions showed that some 12 233 GL year^{-1} (52%) of water is discharged into the estuary and an average of 11 327 GL year^{-1} (48%) is diverted for consumptive use (95% for irrigated agriculture) (CSIRO 2008). An average flow of only 4733 GL year^{-1} has reached the Murray mouth, about a third of natural flows, and flows have ceased since the current dry period began in 2002 (Kingsford *et al.* 2011). River regulation and water diversions have increased the interval between floods, limited the exchanges between rivers and their floodplains, exacerbated low flow conditions, and reduced winter flows and increased summer flows in the southern MDB (Walker and Thoms 1993; Maheshwari *et al.* 1995).

There are likely to be considerable further changes in water availability with climate change and other risks, on the basis of one of the world's more detailed downscale modelling assessments linking climate and hydrology models (van Dijk *et al.* 2006; CSIRO 2008). Estimates of water yield in the MDB for 2030 range for average surface-water availability from +7 to −37%, with median estimated reductions of 12% and 24% in end-of-system flows (Table 1). In the southern MDB, there are predicted declines in autumn and spring runoff with climate change (Fredericksen *et al.* 2010), exacerbating the existing impacts of river regulation (CSIRO 2008). Increased drying has grave implications for loss of flows to the lower River Murray (Kingsford *et al.* 2011). Fire frequency is also expected to increase with climate change (Pittock 2009), potentially further reducing water quality and flows. The regeneration of *Eucalyptus* forests after fires in 2003, the largest of four major bushfires since 2000, which burnt 1 390 000 ha of the headwaters of the MDB is expected to reduce inflows (van Dijk *et al.* 2006).

Past adaptation and sectoral policy measures in the MDB have not adequately considered the whole system, reducing river inflows, and further representing maladaptation (Barnett and O'Neill 2010). Following the capping of surface-water extraction at 1993–1994 levels of development, groundwater use increased considerably, depleting river inflows for surface-water systems connected to groundwater sources (CSIRO 2008). Further, past government incentives for farm-water storage and reticulation (rainwater and irrigation tail-water harvesting) have reduced inflows, as have policies to expand forest plantations (van Dijk *et al.* 2006; CSIRO 2008). As recently as April 2008, government grants were issued to farmers to increase on-farm water storages in the MDB for drought preparedness (WCMA 2008). As governments are urged to revegetate catchments for carbon sequestration and switch to low-emission energy generation technologies requiring additional water (e.g. pumped storage, concentrated solar, and power plants with carbon capture and storage) to reduce the threat from climate change (Garnaut 2008), new water-interception threats will emerge.

Table 1. Changes in estimates of water availability in the Murray–Darling Basin as a result of climate impacts and other risks to water resources (van Dijk *et al.* 2006; CSIRO 2008) and 2009 conditions

CSIRO scenario	Average surface-water availability in 2030 (%)	End of system flows in 2030 (%)
Risks to shared water resources[A]	−10 to −23	n.a.
Extreme wet[B]	+7	+20
Median[B]	−12	−24
Extreme dry[B]	−37	−69
2009 conditions[C]	−66	No outflows since 2002

[A] Earlier estimate from van Dijk *et al.* (2006).

[B] Later estimate from CSIRO (2008).

[C] June–October 2009 inflows compared with the long-term average for these months (and are higher than for the preceding 3 years), an indication of climatic variability (MDBA 2009*a*).

Changes to water quality

The MDB's current water-quality challenges are expected to increase with future climate change, from reduced inflows, increased temperatures and soil erosion from more frequent extreme rainfall events (Pittock 2009). These are likely to exacerbate toxic cyanobacterial blooms (Bowling and Baker 1996; Davis and Koop 2006). Further, ~21% of the lower MDB's wetlands have sulfidic sediments (Hall *et al.* 2006; Baldwin and Fraser 2009) and their recent desiccation has resulted in oxidisation to form sulfuric acid (Kingsford *et al.* 2011). Salinity remains a major and complex problem in the MDB (Jolly *et al.* 2001; Bailey *et al.* 2006). Reduced surface inflows have markedly increased salinity in the lower reaches of the River Murray (Jolly *et al.* 2001). The condition of the Coorong and Lakes Alexandrina and Albert on the lower River Murray has attracted a lot of attention because of low water levels, acidification, increasing salinity and changes in ecological character (Phillips and Muller 2006; Kingsford *et al.* 2011). Climate change is anticipated to exacerbate salinity (Nielsen and Brock 2009).

Modified riverine thermal regimes also have an impact on the ecological processes that support the freshwater biodiversity and require systematic management, including through conservation of riparian vegetation, groundwater flow, environmental flows and dam releases (Poole and Berman 2001; Olden and Naiman 2010). Water releases from the bottom of dams are often 3–12°C colder than natural, reducing river temperatures 100–300 km downstream on the majority of the MDB's major tributaries (Preece and Jones 2002; Preece 2004). This has contributed to the decline of native fish species, because many aquatic species have high water-temperature triggers in their life cycles, needed to stimulate breeding (Sherman *et al.* 2007). Most MDB dams do not incorporate multiple-level off-takes to release water of varying quality from different depths, although they can be retrofitted with mitigation devices to control temperatures (Sherman 2000).

Impacts on biodiversity

Thirteen river valleys in the MDB were rated in very poor condition, seven poor, two moderate and one good in an assessment of fish species, macro-invertebrates and hydrology (Davies *et al.* 2010). The northern valleys were generally better than the southern valleys. On the lower River Murray, 13 regulating weirs have had severe impacts on the fish, mussels, crustaceans and snail species, and exacerbated salinity (Walker 1985, 2006). Reduced inputs of floodplain carbon may have resulted in domination of these rivers by algal production (Robertson *et al.* 1999).

Many of the major wetlands in the MDB are threatened by the lengthening period between ecologically beneficial flood events; this has roughly doubled and now threatens to severely, if not irreversibly, disrupt key ecological wetland values (CSIRO 2008). Tens of thousands of hectares of floodplain forests are in transition to more terrestrial ecosystems (NRC 2009). For example, relative to floodplain-forest conservation targets set in 2003 (Jones *et al.* 2002; MDBMC 2003), four designated 'icon' sites (Ramsar sites) along the River Murray (200 000 ha) continued to degrade in 2006 and 2009 (Table 2; MDBC 2007). The condition of the wetlands at the mouth of the River Murray is particularly grim (Kingsford *et al.* 2011). The ecological condition of other important wetlands across the MDB continues to decline, including the Macquarie Marshes and the Gwydir Wetlands (Kingsford 2000; Kingsford and Auld 2005; Thomas *et al.* in press).

Breeding populations of colonial waterbird species in forested wetlands require inundation of certain depths and duration and timing – usually large flood events if they are to breed successfully – and in other wetlands hydrological variability favours high waterbird biodiversity. The decline in the extent and frequency of flooding across much of the floodplains threatens the survival of the populations that were formerly prevalent in these wetlands (Kingsford and Thomas 2004; Kingsford *et al.* 2004*b*; Kingsford and Auld 2005). Climate change is expected to decrease flood frequency for major wetlands, further threatening waterbirds (CSIRO 2008).

Native fish now make up only 20% of the total catch in regulated rivers in the MDB, as a result of changes in flow regulation disrupting the natural water-regime triggers for fish spawning, thermal pollution and barriers to movement (Gehrke *et al.* 1995; Gehrke and Harris 2001; Growns 2008). The MDB's aquatic biodiversity has also been severely affected by barriers, cutting access to rivers, and flood levees, cutting access to floodplains, with more than 3600 weirs in the MDB that block longitudinal connectivity (Arthington and Pusey 2003). Restoring connectivity will be essential for the movement of aquatic species to more favourable niches with a warmer climate.

Recent responses of governments

The MDB falls within four Australian states and the Australian Capital Territory, which have exercised authority to manage natural resources, including land and water. Since 1983, the Federal Government has increasingly applied indirect constitutional powers to regulate trading corporations and implement national obligations under international treaties to improve environmental management (Connell 2007).

Recent government responses to the deterioration of the river system have focussed on improving environmental water allocations. In 2002, an expert panel appointed by the governments recommended options for a 'healthy working' River Murray (Jones *et al.* 2002), including increasing environmental flows with up to 4000 GL year^{-1} more water providing a 'good' chance of restoring ecological health. Six River Murray wetland 'icon sites' became the focus of conservation efforts (MDBMC 2003, see data on the condition of four of these sites covering 201 700 ha in Table 2), with governments reallocating 500 GL year^{-1} in 2003 to sustain the ecological character of portions (~20% of some wetland types) of the wetland areas of the six sites, and with a 'low–moderate' probability of delivering a healthy river (MDBMC 2003). The modest targets set in 2003 had not been achieved by 2009 (Table 2). In 2004, the National Water Initiative (COAG 2008) was agreed between the state and federal governments, with reforms to reduce water allocations to sustainable levels, provide environmental flows, and consider climate change impacts. In contrast to many resource-use measures, these environmental commitments have been poorly implemented by the states, with inadequate progress towards the

Table 2. Comparison of the forest-stand condition in 2003, 2006 and 2009, compared with government interim ecological objectives for 'healthy' red gum forest set in 2003 and impacts of development for four Living Murray 'icon sites'

Icon	Area (ha)^{A}	Impact on flows^{B}		Objective^{C} (%)	Stand condition					
					All forest 2003^{D}	Red gum 2006^{E}				All forest 2009^{D}
		Increase in average period between beneficial flooding	Average flood volume per year (%)		Good (%)	Healthy^{D}/ good (%)	Declining (%)	Poor (%)	Severely degraded/ dead (%)	Good (%)
Barmah-Millewa Forest	66 000	~2 times	<25	~100^{C}	47.6	20	75	5	0	21.4
Gunbower–Koondrook–Perricoota Forest	50 000	~2 times	17	30	20.6	19	59 'unhealthy'^{G}		22	10.8
Hattah Lakes	48 000	~2 times	17	~50^{F}	6.6	5	19	31	45	3.1
Lindsay and Wallpolla Islands^{H}	20 000	~4 times	39	100^{H}	26.7	21	45	21	12	22.4
Chowilla^{H}	17 700	~4 times	39	100^{H}	14.7	20–60% of all trees are dead or nearly dead, whereas ~90% of live trees are stressed or severely stressed^{G}				13.6
Murray Channel	n.a.	–	Variable	–	39.6	–	–	–	–	28.1

[A] MDBC (2007).

[B] Increase in average period between beneficial flooding and average flood volume per year, compared with a 'without-development' scenario from CSIRO (2008: Section 7.4).

[C] MDBMC (2003). Dual objectives were set for the Barmah–Millewa Forest of healthy vegetation in at least 55% of the overall forest area, including 'virtually all' of the red gum forest (and some other ecological communities).

[D] Data on all floodplain forest stand condition from Cunningham *et al.* (2009, Tables 11 and 12), which detail additional stand-condition categories.

[E] Data on red gum stand condition from MDBC (2007). Red gum stand-condition categories were assessed by using a stand-condition index based on measurements of crown vigour, live basal area, and a plant area index as detailed by Cunningham *et al.* (2007).

[F] The MDBMC (2003) set an objective for 'aquatic vegetation zone' around at least half the 17 lakes to be healthy, and that vegetation is assumed to be red gum riparian forests in this table.

[G] MDBC (2007) do not distinguish between categories of degradation at some sites, and descriptions of these sites are quoted instead.

[H] Administered as part of the Chowilla icon site. The MDBMC (2003) set an objective to 'maintain health of the current area of river redgums', but it is not clear whether they meant the historical area of red gum forest or only the portion that was still alive in 2003.

following: returning over-allocated systems to environmentally sustainable levels of extraction, securing environmental water entitlements, enabling environmental water managers and embedding climate change adaptation measures in water planning and management (NWC 2009).

Governments have consistently provided water to irrigators (CSIRO 2008), and taken actions to conserve freshwater ecosystems; however, they have failed to overcome the past neglect of the environment when managing the water resources. In recent years, all states have purported to implement environmental flows, although inconsistently, and with inadequate target-setting, monitoring and reporting, when long-term implementation is required to halt and begin to reverse the decline of the freshwater ecosystem (NWC 2009). The lack of an agreed vision at the MDB scale, translated into ecological objectives and targets and cascaded down to catchments, coupled with ineffective state conservation processes have contributed to this failure. For example, the *Victorian River Health Program* developed sophisticated, monthly operational rules for each river in 2006, and the New South Wales government developed water-sharing plans. Yet, when the recent drought developed, the New South Wales Government (from 2006) and Victorian Government (from 2007) abrogated environmental-flow agreements (NWC 2009). Environmental-flow rules, suspended when conditions become too dry, are not useful, especially as such conditions are expected to increase with climate change. The Victorian Government developed an 'emergency watering plan' that focussed on 21 'priority aquatic refuge' sites in the Victorian MDB (J. Doolan, pers. comm.), primarily for conservation of threatened species, but effectively abandoned other freshwater ecosystems, including some Ramsar sites. This pragmatic approach was more probably more effective and strategic than the *ad hoc* processes of other states.

By 2006, the looming ecological collapse of the lower River Murray (Kingsford *et al.* 2011) sparked further management reforms. Drawing on the Ramsar Convention and other international agreements, the Federal Government extended the application of its powers to manage water in the MDB under the *Water Act 2007*. A new independent Murray–Darling Basin Authority (MDBA) is required to prepare a Basin Plan (MDBA 2009*b*), including setting 'sustainable diversion limits' (MDBA 2009*c*) for water and an 'environmental watering plan' by 2011, with iterative revisions in later years. The aim is to 'to protect, restore and provide for the ecological values and ecosystem services', including managing risks arising from 'the taking and using of water, the effects of climate change, changes in land use, and lack of knowledge' (MDBA 2009*b*). AU$12.9 billion has been allocated in the *Water for the Future* program, most for the MDB, on top of pre-existing state and federal government programs. The emphasis on water use-efficiency measures has been criticised as economically and environmentally inefficient (Productivity Commission 2010; Young 2010). The AU$3.1 billion allocated in the program for purchase of water entitlements (Wong 2008) is enough to purchase ~1268 GL in average annual water flows, or ~11.2% of the MDB's consumptive water use (Productivity Commission 2010). This would contribute to a total of 2540 GL (or 22.4% of consumptive water use) of likely environmental water recovery under all major existing programs of state and the Commonwealth governments (Productivity Commission 2010). As at 30 June 2010, water entitlements had been purchased that equated to an expected average annual water volume of 591 GL (DEWHA 2010) and wetland areas, including Ramsar sites, have benefitted from small-scale environmental watering.

Targets for the conservation of freshwater ecosystems are being determined. Existing state tributary 'catchment management plans' remain in force up to 2019, despite the urgent need for further action and changes in the way water is managed across the MDB. Further, many reform agreement (COAG 2008) and *Water Act 2007* provisions are vaguely defined, enforcement measures are not clear, or in the hands of the state governments, who have not effectively implemented or policed their own water and environmental laws (Foerster 2008). Importantly, risks and costs for future reductions in water entitlements will be borne by the following: water-entitlement holders for reductions as a result of climate change or 'periodic natural events'; government for changes in government policy; and water-entitlement holders and governments if improvements in knowledge require reductions in water take to achieve environmentally sustainable levels (MDBA 2009*b*). Such provisions are open to interpretation. For instance, distinction between water losses resulting from improvements in knowledge of climate change and consequent changes in government policies is ill-defined.

The Basin Plan is using CSIRO's downscaled hydrological modelling, which reports a considerable range of potential outcomes for water availability (see Table 1). Government plans to manage climate change emphasise a median scenario (MDBA 2009*b*) when the short-term water scarcity in 2009 was more severe that the CSIRO's 2030 'extreme dry' scenario (Table 1; CSIRO 2008). Emphasis would be better placed on reducing the risks of impacts from less likely but catastrophic climate change, including by applying robust, no- and low-regrets adaptation measures.

Future options for freshwater conservation

Re-allocation of more water to the environment is essential for improved freshwater conservation. Any measure to reduce the impact of current threats, including drought, and increase the resilience of freshwater biota to climate change is helpful (Bond *et al.* 2008). Governments will need to implement the hard reforms they have avoided, such as regulating groundwater use, closing legal loopholes (such as unregulated diversion of 'overland flows'), and enforcing existing policies (Foerster 2008; Young 2010). It is essential to avoid maladaptation to climate change where other sectoral policies exacerbate impacts on freshwater ecosystems (Pittock *et al.* 2008; Barnett and O'Neill 2010). For example, incentives for carbon sequestration, resulting in re-afforestation of catchments, are expected to reduce flows (Herron *et al.* 2002; van Dijk and Keenan 2007).

The freshwater ecosystems of the MDB developed with all the naturally available water and so reductions as a result of diversions are producing a considerable loss of biodiversity, which may be exacerbated by climate change. On the extensive, low-elevation floodplains in the MDB, the return interval of flood pulses and the hydrological gradient determine the extent and distribution of wetland ecosystems. Value judgments are required as to how much of the freshwater ecosystems to conserve versus diversion of water and, with climate change, there has been a call to 'downsize' the river system (Young and McColl 2008; WGCS 2010). A robust form of triage is required to identify the freshwater ecosystems that can be most readily conserved with the available water and are representative of the range of ecosystems, resulting in re-sizing of the socioeconomic and ecological systems. Internationally, methods exist for assessing, prioritising and protecting key freshwater ecosystems (Abell *et al.* 2007; Nel *et al.* 2007; Thieme *et al.* 2007), although these will require adaptation to accommodate the effects of climate change on freshwater ecosystems (Hansen *et al.* 2003; Pittock *et al.* 2008).

In Australia, only Victoria has comprehensively assessed freshwater conservation values and established relevant protected areas and conservation measures (e.g. VEAC 2008), mostly without consideration of the effects of climate change. Despite obligations under the Ramsar Convention on Wetlands, the Convention on Biological Diversity and national policies, no representative reserve system for the MDB's freshwater biota has been established (Nevill 2007; Pittock 2008). There remains a conflict between the modest conservation goals ('triage') set in plans such as *The Living Murray* sites and for Victorian priority aquatic refuges, with broad, national, conservation obligations under the Ramsar Convention – to maintain the ecological character of wetlands – and other treaties underpinning the *Water Act 2007*. These conflicts need to be addressed with more ambitious conservation targets.

Governments and societies need to decide how much of the freshwater environment to conserve and what targets to set for conservation (Wishart 2006). Most public discussion in the MDB has focussed on water allocations (Wong 2008; WGCS 2010); however, increasing environmental flows needs to be complemented by other strategies to maximise the conservation benefits for freshwater ecosystems. Climate change resilience requires identification and conservation of river systems with favourable altitudinal and longitudinal gradients, whose aspect may mitigate changes in thermal regimes (Poole and Berman 2001), and where connectivity may aid movement of biodiversity. Regulated river systems with substantial water flows (CSIRO 2008) and free-flowing rivers (Pittock *et al.* 2008) will also be more resilient. Another adaptation option may be to enhance conservation of freshwater biodiversity through groundwater inflows as climate change 'will have very small impacts on water exchange between aquifers and rivers' (CSIRO 2008). These gaining river reaches (i.e. sections of the rivers where there is a net movement of groundwater to surface water) are thus partly insulated from the greater hydrological variability induced by climate change (Poole and Berman 2001; CSIRO 2008). Although groundwater cannot provide flood pulses, we postulate that improved management of groundwater may help sustain floodplain and riparian vegetation, and in-channel refugia (Poole and Berman 2001; Sheldon *et al.* 2010) and would require the current over-use of many groundwater aquifers to be stemmed (NWC 2009).

Effective freshwater conservation with a changing climate requires additional measures to be included in the 2011 Basin Plan. There are six place-based adaptation actions recommended globally for river ecosystems, including the following: monitoring and forecasting, enhanced technical assistance, increased protection of rivers, conjunctive management of groundwater, restoration, and diversification and replication of habitats and populations in protected areas (Palmer *et al.* 2008). These actions could be incorporated into a framework for conservation that should also include climate change adaptation benefits from conservation of free-flowing or unregulated rivers (unfragmented rivers, Nilsson *et al.* 2005), and the risks and opportunities of different environmental water management strategies (Pittock and Lankford 2010). We propose five adaptation measures to manage rivers in response to climate change in the MDB (Table 3). Management measures are needed to conserve all rivers, with more specific adaptation strategies required for a disturbance spectrum extending from little-disturbed, free-flowing rivers through to highly affected regulated rivers.

Institutional and technical capacity is required to manage all the MDB's rivers to enable them to adapt to climate change (Palmer *et al.* 2008; Table 3). The Basin Plan should incorporate fine-scale physical ecosystem restoration and conservation measures that build resilience against additional climate change impacts (Table 3). Standards for ecologically successful river restoration have been proposed, and although they do not explicitly consider climate change, they can build resilience (Palmer *et al.* 2005; Jenkins and Boulton 2007). These include restoration of riparian vegetation, reduction in sediment and pollution loads, and establishment of freshwater-protected or refuge areas (Bond *et al.* 2008; Nelson *et al.* 2009). Institutionally, these adaptation interventions will be complex and resource-intensive, apply low-technology measures and require ongoing action (e.g. involvement of adjacent landholders in weed control).

Free-flowing rivers are little affected and retain ecosystem processes, such as natural flow variability and connectivity, damaged in regulated rivers (Nilsson 1996). Consequently, these riverine ecosystems are probably more resilient to climate change impacts, including having healthy riparian forests with favourable microclimates that resist climate change-induced temperature extremes (Poole and Berman 2001). Also, the lack of barriers may enable biota to move to new habitat niches. Risks still remain in exceeding climate change impact thresholds (e.g. changes to water quantity and quality), beyond which particular biodiversity may not survive. In the absence of infrastructure, further options for management interventions to conserve pre-climate change river ecosystems may be limited. The largest examples of free-flowing rivers in the MDB are the Paroo and Ovens rivers, which are subject to negligible water diversions (CSIRO 2008). Free-flowing rivers may require limited management intervention to retain their conservation values; however, legal protection is a priority (Table 3). Victoria's *Heritage Rivers Act 1992* and Queensland's *Wild Rivers Act 2005* provide state legislative models for conserving such rivers. Although some individual wetlands are designated Ramsar sites in the Paroo catchment, the Federal Government has not applied the Ramsar and national heritage provisions of the *Environment Protection and Biodiversity Conservation Act 1999* to more fully conserve such free-flowing systems.

Similarly, large free-flowing tributaries in some MDB subbasins may provide good longitudinal connectivity and naturally variable flows for downstream wetlands, despite large dams

Table 3. Climate change adaptation measures for conservation of freshwater ecosystems: components, implementation requirements and risks (adapted after Palmer *et al.* 2008)

Scope	Adaptation measures	Components	Implementation requirements	Main risk/s
All rivers	Institutional and technical capacity	Research, monitoring and assessment Management institutions Integrated river-basin management Trained managers Financing for management	Laws, knowledge and funding	Inadequate societal, political and legal support
	Physical management	Restoration and resilience building of river catchments and riparian corridors, including inflow management, water-quality management, vegetation conservation, protected areas and invasive species control	Complex institutions and technical capacity	Climate change impacts are too large and/or fast for the freshwater ecosystem to resist or adapt Institutional failure
Through the spectrum of river conditions, from free-flowing to regulated	Conservation of free-flowing rivers	Designation under laws to reserve wild, scenic or heritage rivers	Reliance on legal protection	Climate change impacts are too large and/or fast for the freshwater ecosystem to adapt; inadequate legal protection
		Legal protection against water-resources development	Modest investment in low-technology catchment and riparian conservation measures	
		Ecological processes maintained and restored	Little day-to-day management intervention	
	Restoring and protecting key tributaries, management in conjunction with regulated river/s	Legal protection for free-flowing tributaries	Initial investment in restoration	Failure to conjunctively manage free-flowing and regulated streams
		Strategic removal or re-operation of water infrastructure	Conjunctive management requires high technology and day-to-day management interventions	Risks from both free-flowing and regulated approaches, but spread through diversity of measures
		Use of naturally variable flows and connectivity to sustain downstream ecological processes in conjunction with operation of regulated river/s		
	Reoperating regulated rivers	Periodic re-licensing of water infrastructure	Large initial investment in restoration	Institutional failure
		Provision of environmental flows, fish passage, thermal pollution control	High-technology interventions	
		Downstream environmental water-demand management measures	Extensive day-to-day management interventions required	

fragmenting the main stems of these rivers (Table 3). Modest-sized floods from such unregulated tributaries have been extended by regulated environmental flow releases for key ecological objectives, such as the fledging of colonial waterbird chicks in the Gwydir wetlands (Wilson *et al.* 2010). Unregulated floods could act as a catalyst for management, such as in the Gwydir valley where the Horton River (Fig. 1) and small creeks provide nearly a quarter of the Gwydir River flows below Copeton Dam in an average year (DWR 1993). The importance of allowing unregulated flows through to the Gwydir wetlands is partially recognised (up to 500 ML day^{-1}) in the New South Wales Government's *Water Sharing Plan for the Gwydir Regulated River Water Source 2002*, although implementation of rules for conjunctive management of free-flowing and regulated rivers has been problematic (Foerster 2008). Another example is the importance of unregulated flows from the Talbragar River (Fig. 1) in maintaining the Macquarie Marshes on the highly regulated Macquarie River, a critically important river system in terms of volume and variability (although the use of these flows for conservation would require a change in river management rules) (B. Johnson, pers. comm.). Similar international examples exist, such as the Palmiet River in South Africa where the free-flowing Dwars and Louws tributaries keep the lower river in largely natural condition, compared with the degraded, regulated upper reaches (Fowler *et al.* 2000). Unregulated tributaries in the MDB may not be especially biodiverse and are often affected by water diversions and other anthropogenic impacts, but their prioritisation for conservation would aid the maintenance of ecosystem processes, such as flow variability, longitudinal connectivity and geomorphological processes. The Murray–Darling Basin Authority is proposing to identify key ecological assets as priorities for conservation, mainly large floodplain wetlands in its Basin Plan, with no indication of prioritising unregulated tributaries for conservation. To implement this approach, legal reservation and a modest up-front investment is required to protect and restore free-flowing tributaries and gaining reaches. Once these measures are established, the biggest management challenge may lie in effective management of water releases in the regulated portion of the sub-basin to complement flows from the free-flowing sections (Foerster 2008).

Conservation could also focus on gaining river reaches (CSIRO 2008). Reaches are a focus for conservation of particular fish species, such as salmonids in the United States through maintenance of water flows and water temperatures (Poole and Berman 2001). Also, there are Australian commitments to conserve groundwater-dependant ecosystems through the *National Water Initiative*; however, there is little evidence of this occurring in the MDB (NWC 2009) outside of the Great Artesian Basin. Protection of groundwater inflows into surface systems in the MDB may be important in the face of climate change, providing water quantity and (freshwater) quality, although relatively little is known of this contribution. Prioritisation and protection of relevant gaining reaches such as reduction of groundwater extraction should be considered under the ecological assets and ecosystem services provisions of the *Water Act 2007*.

Last, control provided by water infrastructure can help conserve freshwater biota of regulated rivers and their floodplains under climate change (Table 3). The provision of environmental flows is widely advocated (Rood *et al.* 2005; Poff *et al.* 2010), including for climate change adaptation (Palmer *et al.* 2008). There are risks of institutional failure in relying entirely on environmental flow arrangements. The 'suspension' of environmental flow agreements by the Victorian and New South Wales Governments since 2006 (NWC 2009) highlights this danger. Australian governments also aim to improve ecological health of rivers, with demand-management measures for the environment, such as the use of weirs, levees, channels and pumps to distribute limited volumes of water over broad areas to increase environmental benefits (Pittock and Lankford 2010; Watts *et al.* 2011). These re-operation opportunities have received little attention. Dam infrastructure and operating rules can be modified to provide environmental flows and water releases of a benign temperature to counter some climate impacts (Pittock *et al.* 2008; Krchnak *et al.* 2009). The latter may be difficult because of the difficulty in predicting outcomes and potential to release abnormally warm water during winter in North America and affect biota (Olden and Naiman 2010). In the MDB, interventions to improve thermal regimes may be more successful, given that the primary concern now is the release of overly cold water.

Restoration of wildlife passage past in-stream barriers is another important conservation measure. One-off projects have identified barriers for fish-passage restoration in the MDB, such as the 'Sea to Hume Dam' program in the River Murray (Barrett 2008) and assessments of some catchments in New South Wales (NSW DPI 2006), although systematic programs are lacking. To comprehensively address this issue, Australian governments need to adopt periodic water-infrastructure re-licensing laws to meet safety standards to manage more extreme events from climate change (Pittock and Hartmann 2011), similar to those of the Federal Energy Regulatory Commission in the USA (Bednarek 2001; Viers and Rheinheimer 2011). This could be the catalyst for removing redundant regulatory structures and retrofitting others with devices to reduce environmental impacts, including for climate change adaptation (e.g. fish passages, thermal pollution control devices). The re-operation of river infrastructure will initially require expensive and high-technology interventions, such as to add multi-level off-take towers to dams, with ongoing dedication of resources for effective day-to-day management.

Conclusions

Australia's Murray–Darling Basin is vulnerable to the impacts of climate change on freshwater ecosystems, especially in its southern catchments, subject to increasing temperature and declining rainfall. To maximise adaptation, there is need to reduce non-climate impacts on all rivers (e.g. high diversions) to increase resilience to the additional impacts of climate change. A priority should be the conservation of the rivers and other wetlands with the most resilient and adaptive qualities such as by establishing representative freshwater-protected areas. Measures that differentially target rivers depending on their degree of regulation are also required. This includes conserving the MDB's remaining free-flowing rivers and implementing systematic measures to renovate water infrastructure and use it to counter climate change impacts where possible on regulated rivers.

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