CSIRO PUBLISHING

www.publish.csiro.au/journals/mfr *Marine and Freshwater Research*, 2011, **62**, 217–222

Conservation management of rivers and wetlands under climate change – a synthesis

Richard T. Kingsford

Australian Wetlands and Rivers Centre, School of Biological, Earth and Environmental Science, University of New South Wales, NSW 2052, Australia.
Email: richard.kingsford@unsw.edu.au

Abstract. Dams, diversion of water, invasive species, overharvesting and pollution are degrading rivers and wetlands. Climate change may exacerbate impacts of these threats through predicted reductions in rainfall and increased temperature, decreasing flow and altering timing and variability of flow regimes. Papers in this special issue identify conservation-management strategies for wetlands and rivers through recovery of flow regimes, alteration of dam operations, protected-area management and improved governance and adaptive management. On most regulated rivers, flow regimes should be recovered by increasing environmental flows. Alteration of dam operations can also improve river health through structures on dams (e.g. fishways, multi-level offtakes), reinstating floodplains and improving flow delivery. Further, time-limited licensing for dams and accompanying regular assessments of safety and of environmental and socioeconomic impacts could improve operations. Protected areas remain the core strategy for conservation, with recent improvements in their identification and management, supported by analytical tools that integrate across large spatial and temporal scales. Finally, effective conservation requires good governance and rigorous adaptive management. Conservation management of rivers and wetlands can be significantly improved by adopting these strategies although considerable challenges remain, given increasing human pressures on freshwater resources, compounded by the impacts of climate change.

Additional keywords: adaptive management, dam operation, environmental flow, protected areas, river regulation.

Introduction

The world's rivers and wetlands are degrading at an alarming rate, more than other ecosystems (Millennium Ecosystem Assessment 2005), seriously affecting biodiversity (Dudgeon *et al*. 2006; Vörösmarty *et al*. 2010) and human-subsistence communities dependent on river flows (Lemly *et al*. 2000). The causes are well known widespread threats, including habitat loss and degradation, invasive species, overharvesting and pollution (Allan and Flecker 1993; Dudgeon *et al*. 2006), whose impacts may be altered by climate change, which is predicted to change flow regimes to rivers and wetlands (Milly *et al*. 2005; Bates *et al*. 2008; Palmer *et al*. 2008). Cumulative evidence of degradation, loss of ecosystem services and increasing financial burdens of dealing with ecological freshwater problems (e.g. deteriorating water quality) are forcing communities and governments to consider strategies for conservation management. These are necessarily intertwined with water-management objectives for human requirements, often the cause of degradation.

Conservation-management objectives for freshwater ecosystems, particularly for highly regulated rivers where there is extraction, usually have to compete with a legacy of water-resource development for water supply and hydroelectricity generation from rivers, which continues to dominate decision-making on rivers (Vörösmarty *et al*. 2000). Inevitably, conservation management of rivers and wetlands needs to extend well beyond the traditional approach of management of protected areas, communities and species, including those with threatened status. It has to deal with protection or recovery of flow regimes, complicated by effects of climate change. Until recently, water management has assumed that rainfall fluctuates within historical limits of variability, an assumption that has demonstrably failed with climate change (Milly *et al*. 2008). Climate change is projected to alter runoff and water availability by 2050, increasing at high latitudes by 10–40% and decreasing over dry regions by 10–30%, as well as increasing extremes of dry and wet periods (IPCC 2007). This will particularly affect wetlands and rivers predicted to become drier and may also offer opportunities where runoff and water availability are predicted to increase. Regulated river basins are predicted to be affected more than free-flowing river basins (Palmer *et al*. 2008). Although other threats to freshwater ecosystems can be substantial, modification of flow regimes remains the most widespread problem for rivers and wetlands. In this special issue, 10 papers examine threats facing rivers and wetlands and outline conservation-management strategies, including recovery of flow regimes, alteration of dam operations, management of protected areas, and effective governance and adaptive management. Here, I synthesise the different perspectives on conservation-management strategies for wetlands and rivers, given increasing effects of climate change.

10.1071/MF11029 1323-1650/11/030217

Interaction of climate change and other threats

Temperatures are rising and contributing to a changing climate, altering relationships among rainfall, runoff and flows to surface and groundwater systems and increasing aridity of river basins (Milly *et al*. 2005; IPCC 2007). Predicted patterns in global rainfall patterns are considerably uncertain (Bates *et al*. 2008). In Mediterranean rivers, temperatures are increasing whereas rainfall is decreasing (Hermoso and Clavero 2011). The timing, magnitude and frequency of rainfall or snowmelt in many catchments is predicted to change (Bates *et al*. 2008; Milliman *et al*. 2008; Klausmeyer and Shaw 2009; Palmer *et al*. 2009; Viers and Rheinheimer 2011), with increasing temperatures predicted to augment flows early in spring as snowpacks melt and produce flow reductions in summer (Aldous *et al*. 2011). This inevitably increases availability of aquatic habitat downstream in spring, and reduces this habitat in summer.

Environmental envelopes or niches for biota will change with climate change. High temperatures and changes to hydrologic regimes may exceed tolerances of some aquatic biota (e.g. reduced perenniality, increased water temperatures of mountain streams, Palmer *et al*. 2009; Turak *et al*. 2011; Viers and Rheinheimer 2011). With reduced rainfall from climate change, there will be increased drying of rivers and wetlands (Herron *et al*. 2002), and this will be exacerbated by decreasing durations of flooding caused by rising air temperatures, compounding effects of flow reductions from regulation. Such effects will not be as severe as the impacts of river regulation (Lester *et al*. 2011). There are already major regime shifts in many aquatic ecosystems from changes to flow produced by river regulation (Gordon *et al*. 2008). Increased fragmentation provides opportunities for weed invasion. For example, the prostrate-growing plant lippia, *Phyla canescens*, has invaded and established almost mono-specific stands in parts of the Macquarie Marshes and Gwydir wetlands as a result of reductions in flooding (Whalley *et al*. 2010).

For coastal rivers and wetlands, sea-level rises are likely to affect freshwater wetland systems, as intruding seawater tips low-lying coastal freshwater wetlands into an alternate state (i.e. from freshwater to estuarine or marine, Turak *et al*. 2011). Obligate freshwater species will be replaced by more marine-tolerant biota as the sea invades these freshwater ecosystems (Kingsford *et al*. 2011*a*). Impacts of pollution are also likely to increase if freshwater flows decrease to rivers and wetlands (Palmer *et al*. 2009; Hermoso and Clavero 2011). For example, acidity and salinity increased considerably above natural levels on the Ramsar-listed Coorong, Lower Lakes and Murray Mouth wetland of the Murray–Darling Basin, with reductions in freshwater flows (Kingsford *et al*. 2011*a*).

Strategies for conservation management

Conservation management should vary with the nature and scale of threats across a catchment. Effects of invasive species, pollution and overharvesting usually demand a local focus. Protection and rehabilitation of flow regimes represents the greatest challenge for conservation of most rivers and wetlands. Opportunities to protect free-flowing rivers and tributaries should be implemented wherever possible to increase catchment-scale resilience (Palmer *et al*. 2008; Pittock and Finlayson 2011; Viers and Rheinheimer 2011). Also, with burgeoning human populations and increased dry periods and more-severe flooding with climate change, demands to develop water resources will continue (e.g. Okavango River Basin, Milzow *et al*. 2009). Environmental impacts should be adequately assessed across ecological and socioeconomic dimensions (e.g. flooding of agricultural land; impacts on fisheries; Gleick 2003). Conservation-management strategies to improve flow regimes include recovery of flow regimes, alteration of dam operations, protected-area management, and governance and adaptive management (Table 1).

Recovery of flow regimes

River regulation by dams and weirs and floodplain earthworks has fragmented hydrological and ecological processes (Nilsson *et al*. 2005), often severing or restricting connectivity to rivers and wetlands (Lemly *et al*. 2000; Kingsford *et al*. 2006). Consequently, recovery of flow regimes has become a key strategy for conservation, partly recovered by increasing environmental flows (Arthington *et al*. 2006). At their minimum, environmental flows are defined as water remaining in rivers after extraction for human use (e.g. Mediterranean rivers, Hermoso and Clavero 2011); however, there is increasing understanding that most current environmental flows inadequately sustain downstream ecosystems in highly regulated river basins (Aldous *et al*. 2011; Kingsford *et al*. 2011*a*). Legal recognition of environmental flows remains an important first step, albeit not universally recognised (Hermoso and Clavero 2011).

Environmental flows need to be established in all regulated rivers and increased considerably to meet legislated conservation obligations (Table 1). For example, the Murray–Darling Basin Authority (MDBA) estimated that full ecological sustainability of the Murray–Darling Basin rivers would require increased annual environmental flows of an average of 7600 GL; however, MDBA recommended 3000–4000 GL because of the likely socioeconomic impact (MDBA 2010). Given the limited water for environmental flows available in many rivers, environmental flows will need to focus on key ecosystems and processes (Table 1). Sophisticated modelling tools, applicable at large spatial and long temporal scales, will be critical for decision-making, linking hydrology to ecology and socioeconomic indicators (Table 1). Such modelling is often constrained by relatively poor fine-scale climate-prediction models, with few river basins having adequate numerical models (Aldous *et al*. 2011).

Alteration of dam operations

Conservation-management strategies focussed on alteration of dam operations can improve environmental outcomes for rivers and wetlands (Palmer *et al*. 2008; Table 1). Flow regimes of regulated rivers are managed, largely through the operation of dam storage and release and downstream weirs, and by reregulating storages. Traditionally, the building of dams and their operation in the catchment have focussed on providing water for human uses and not for the environment. Increasingly, climate change, through predicted increased rainfall variability, intensification and reduction, will require evaluation of dam safety around the world, particularly assessing their ability to cope with increased frequency of large flood events (Bates *et al*. 2008).

Table 1. Description and scale of implementation of conservation-management strategies for addressing alteration of flow regimes for free-flowing to highly regulated rivers and wetlands in the face of climate change

Superscripts indicate which papers in the special issue discuss the strategies

Initiative	Description	Scale
Recovering flow regimes	Protect flow regimes of rivers and tributaries that remain largely free-flowing[A,B]. Ensure good environmental and socioeconomic assessments of new and old dams and increasing diversions from rivers[C], including incorporating modelling that identifies tradeoffs[D]. Establish environmental flows to regulate rivers that are legally protected[A,E]. Increase environmental flows to meet conservation obligations for key processes, protected areas, significant habitat areas or internationally important wetlands listed under the Ramsar Convention[A,B,C,E,F,G,H]. Improve modelling to produce scenarios that allow for complex temporal decision-making between deleterious human changes to flow regimes and environmental consequences, given effects of climate change (e.g. irrigation diversions; hydroelectricity generation alterations to flow)[D,G,F].	Scale may vary from individual wetlands to entire river catchments, ranging from altered to free-flowing flow regimes.
Alteration of dam operations	Introduce time-limited licensing for all dams through legislation, allowing for regular (~30 years) reviews of safety and risk of failure and socioeconomic and environmental impacts[B,C]. Retro-fit structures to dams to improve environmental outcomes, including multi-level offtakes to improve downstream water temperatures and fishways that allow movement of organisms past dam walls[B,C,F]. Pulse flows to mimic natural flow regimes, during delivery of flow between dams or for human use[I]. Identify opportunities for rehabilitation of floodplains, with dam operations to mitigate flooding impacts (may require purchase of floodplain easements)[A,B,F,I]. For cascades of dams, investigate opportunities to reregulate flows by capturing flows in the lowest dam of the cascade and then release flow to mimic natural flow patterns[A,B,I]. Investigate opportunities for groundwater storage with dam storage[I]. Implement structural modifications, including pumping of environmental water and adjustments to weir levels to produce flooding of wetlands and floodplains[A,G]. Establish river operations that allow for 'piggy-backing' of environmental flows with diversions for human use, providing increased opportunity for environmental flows to flow over banks and reach floodplains and wetlands[I]. Alter delivery of water to riparian users that mimics natural flow regimes and can contribute to water savings for environmental use[I].	All rivers with dams should have time-limited licensing while dam and river operations will vary depending on the opportunities provided in each regulated river system.
Protected-area management	Increase identification and gazettal of freshwater protected areas as a key focus for management of rivers and wetlands throughout a catchment, using rigorous conservation planning[D,E,J]. Ensure that legislative conservation obligations are met and, in particular, ecological values are protected or rehabilitated by providing sufficient environmental flows to meet defined ecosystem targets[A,E,F]. Apply conservation-planning approaches, including comprehensiveness, adequacy, representativeness and efficiency, from a catchment to broad jurisdictional scale to identify priority habitats for designation and management as protected areas or for mitigation of threats or to potentially establish priorities for flow delivery[D,J]. Build biological databases that provide spatial and temporal information for conservation planning[B,D,J].	Applies across the full range from free-flowing to highly regulated river catchments and wetlands.
Governance and adaptive management	Integrate different responsibilities at the catchment scale, so there is a coherent approach to policy and management[B,D,F,G]. Implement conservation legislation that supports resilience of rivers and wetlands, including limiting effects of regulatory structures (e.g. wild rivers legislation, adequate environmental assessment, environmental flow)[A,B,C,E]. Establish and implement adaptive management[F,I] (e.g. Strategic Adaptive Management Plan; Kingsford *et al*. 2011*b*), involving all stakeholders and including the following steps: (1) determine desired condition (goal, hierarchy of objectives, indicators); (2) identify management options for a suite of objectives; (3) operationalise management; and (4) evaluate and learn, including reporting on outcomes of conservation management for ecosystems to ensure transparency and accountability (i.e. long-term indicators of environmental health).	All wetlands, rivers and catchments, whether highly regulated or free-flowing.

[A]Pittock and Finlayson (2011); [B]Viers and Rheinheimer (2011); [C]Pittock and Hartmann (2011); [D]Nel *et al*. (2011); [E]Hermoso and Clavero (2011); [F]Kingsford *et al*. (2011*a*); [G]Aldous *et al*. (2011); [H]Lester *et al*. (2011); [I]Watts *et al*. (2011); [J]Turak *et al*. (2011).

This may be a catalyst to re-examination of safety risks of dams, including operating air spaces and pre-releases (Pittock and Hartmann 2011). Many thousands of dams require maintenance each year as they age and lose efficiency and this provides an opportunity to assess whether such structures still meet their purposes through establishment of a relicensing framework (Pittock and Hartmann 2011). The Federal Energy Regulatory Commission in the USA operates ~1000 hydropower dams, with time-limited licensing and accompanying socioeconomic and environmental assessment (Pittock and Hartmann 2011; Viers and Rheinheimer 2011), resulting in dam removal and refurbishments to reduce environmental impacts. In the Klamath basin, a proposed restoration agreement provides for removal of four hydroelectric dams (Aldous *et al*. 2011).

Climatic changes and resulting altered flow regimes can also force re-examination of river operations (Viers and Rheinheimer 2011), including modifying dams with structures to improve biodiversity conservation (Table 1). These can include building multi-level offtakes to overcome thermal pollution downstream (Pittock and Hartmann 2011; Viers and Rheinheimer 2011) and fishways to improve fish passage. Some dams (e.g. Burrendong Dam, Macquarie River, Australia) have limitations on the quantity of environmental flow that can be released, constraining environmental-flow management; this could be rectified by increasing the size of the outlet. Also, different dam and river operations (e.g. linking dams, aquifer storage) can deliver environmental benefits, more closely mimicking natural flow regimes without necessarily affecting allocations of water to consumers and the environment (Watts *et al*. 2011). Such flows can target geomorphic and ecological processes and aquatic species (Table 1). Reinstating connectivity to wetlands such as natural floodplains can also mitigate effects of floods (Table 1). For example, in the Savannah River (USA), bypassing the city of Augusta in times of high flow events could restructure and rehabilitate floodplain habitats and reduce flood damage (Aldous *et al*. 2011). Operational changes may require purchase of floodplain easements to allow for periodic flooding.

There may also be opportunities to reregulate flows to mimic the natural flow regime once water has passed through a sequence of dams for hydroelectricity generation, using the most downstream dam to reregulate towards a more natural flow regime (Table 1). Sometimes structural modifications to distributary systems and installation of pumps are required. For example, a large pump on the River Murray transfers water into slightly modified natural channels that deliver environmental flows to Hattah Lakes on the River Murray, whereas changes to weir levels can raise river heights sufficiently to allow inundation of downstream floodplain forests (Aldous *et al*. 2011).

Protected-area management

Many protected freshwater areas are in decline, failing to meet basic objectives for conservation, largely because of effects of water-resource management (Hermoso and Clavero 2011; Kingsford *et al*. 2011*a*; Pittock and Finlayson 2011). Where climate change reduces flows, the problems will be exacerbated (Hermoso and Clavero 2011; Lester *et al*. 2011). The gazettal of protected areas, often accompanied by listing as wetlands of international importance under the Ramsar Convention, remains a core conservation strategy, applicable across rivers with flow regimes ranging from free-flowing to highly regulated. The key problem with protected-area management is the lack of control over the flow regime, which underpins a freshwater protected area's resilience. Without protection of flows, resilience of freshwater protected areas will fail as upstream water-resource development increases or flow decreases further with climate change.

Traditionally, conservation management of ecosystems and biota has relied on a protected-area approach; however, there is increasing realisation that mitigation of catchment processes remains the fundamental challenge for effective conservation management of rivers and wetlands. Protected-area status ascribes conservation responsibility to government, usually through its conservation agency, with associated legislative responsibilities. Protected-area gazettal and management often represents the most obvious government commitment to conservation, even though inclusion of freshwater ecosystems may be incidental to scenic or terrestrial landscapes (Kingsford *et al*. 2011*b*; Viers and Rheinheimer 2011). After key freshwater habitats are identified, they can be protected formally or become targets for the management of threatening processes and environmental flows. Priorities for protection should be refugia, key habitats and dispersal corridors for aquatic species, given the projected impacts of climate change (Turak *et al*. 2011). On free-flowing rivers, protected areas can become an important node for assessing impacts of upstream development (Kingsford *et al*. 1998). Even where threat management is not effective (e.g. as a result of river regulation and extraction upstream), building evidence of degradation of freshwater protected areas can become a powerful incentive for governments to commit resources (e.g. Coorong, Lower Lakes and Murray Mouth, Kingsford *et al*. 2011*a*). Protected wetland systems have become the key focus for increased environmental flows in the Murray–Darling Basin (MDBA 2010; Kingsford *et al*. 2011*a*; Pittock and Finlayson 2011) where flow requirements may be defined by flooding requirements of ecosystem components (e.g. good condition of river red gum forests, Aldous *et al*. 2011; Pittock and Finlayson 2011).

Increasing the number of rivers and wetlands in the protected-area network should be a priority (Table 1), given their under-representation in the protected-area network (Kingsford *et al*. 2004; Aldous *et al*. 2011; Hermoso and Clavero 2011). Thus, a key aim must be to produce a comprehensive, adequate, representative and efficient protected-area system where conservation objectives are maximised (Fitzsimons and Robertson 2005; Nel *et al*. 2009, 2011). Conservation-planning tools exist to determine the effectiveness of current and future protected-area networks in protection of biodiversity; however; increased investment is required to build the biological databases that underpin these quantitative approaches (Table 1). For example, limited data on the spatial and temporal distribution of freshwater biodiversity limit application of conservation planning in Sierra Nevada (Viers and Rheinheimer 2011). Traditionally, divergent scientific and assessment fields have existed for environmental-flow management and protected-area identification and designation; however, conservation-planning algorithms can also link to flow assessments (Nel *et al*. 2011).

Governance and adaptive management

Ultimately, political will and successful integration of the plethora of legislative tools and responsibilities for river and wetland management will determine whether there is improved conservation management of freshwater ecosystems. Increasingly, governments are engaged in major freshwater-rehabilitation initiatives (e.g. Murray–Darling Basin in Australia (MDBA 2010; Kingsford *et al*. 2011*a*; Pittock and Finlayson 2011) and European rivers through the Natura 2000 network (Hermoso and Clavero 2011)). The watershed or catchment scale for management remains the key spatial framework, although some strategies can apply within sub-basins (Table 1). Catchments often transcend political boundaries, increasing the number of institutions and legislative instruments water-management interests, including competing water-resource development and conservation objectives which are seldom resolved (Kingsford *et al*. 2011*a*; Hermoso and Clavero 2011; Viers and Rheinheimer 2011). Further, laws and regulations for conservation management of freshwater ecosystems are often badly implemented (Viers and Rheinheimer 2011) or poorly developed (Hermoso and Clavero 2011). For effective conservation management, implementation of existing legislation related to protection of free-flowing rivers, adequate environmental assessment and reduction of impacts of regulatory structures are critical (Table 1). Ultimately, integration of different governance, legislative and regulatory frameworks is essential for effective conservation (Table 1). Strategic adaptive management planning offers some opportunities; however, these have seldom been realised (Poff *et al*. 2003; Kingsford *et al*. 2011*b*).

High-level conservation objectives usually exist for protected areas and some river systems; however, it is often difficult to determine whether these are achieved and so there is a lack of accountability. Strategic adaptive management provides a useful framework that provides for stakeholder engagement and involvement. It links high-level objectives to targets, indicators and thresholds of potential concern to management, promoting transparency and accountability in management, underpinned by ongoing learning (Biggs and Rogers 2003; Kingsford *et al*. 2011*b*; Table 1). A key objective for improving conservation is increased cooperation among scientists, managers and other stakeholders (Poff *et al*. 2003), although performing experiments at the catchment scale remains largely unachievable (Kingsford *et al*. 2011*b*). Strategic adaptive management should begin with stakeholders involved in determining the desired condition for a particular river and wetland and then deriving objectives for its long-term planning and management (Kingsford *et al*. 2011*b*). Such a framework can also be applied to dam operations (Viers and Rheinheimer 2011; Watts *et al*. 2011). It also aims to avoid tipping points for alteration of states, potentially by predicting change using available data and models and effecting appropriate management. Effective implementation requires commitment by managing organisations and rigorous application of hierarchical planning, testing of management and reporting on effectiveness by measuring and modelling ecosystem responses to conservation management (Table 1).

Conclusions

There are many factors degrading rivers and wetlands; however, the most pervasive and deleterious is alteration of flow regimes, primarily driven by appropriation of freshwater for human use, considerably exceeding any effects of climate change on flow regimes (Vörösmarty *et al*. 2000, 2010; Lester *et al*. 2011). Predicted climate-change impacts offer increased challenges for drying systems and prospects for flow improvements where flows may increase.

Recovery of environmental flows and alteration of dam operations provide clear opportunities for proactive conservation of rivers and wetlands, given the uncertainties around impacts of climate change. Protected-area management will remain a key conservation strategy for influencing conservation management; however, long-term resilience depends ultimately on ensuring that flow regimes are improved or protected. The governance and adaptive management frameworks remain the key mechanism providing the institutional impetus for improving conservation management, accompanied by improved modelling of scenarios. Strategic adaptive management can provide practical mechanisms for implementation involving stakeholders, integrating legislative and policy tools, engaging science and imposing accountability on management. The conservation strategies outlined in this special issue can improve the poor state of the world's rivers and wetlands; however, implementation will require considerable effort and focus.

Acknowledgements

The genesis of this special issue was a meeting of freshwater scientists at Goolwa, at the mouth of the Murray–Darling Basin, in 2009, supported by the Australian Wetlands and Rivers Centre, the Water Initiative at the Australian National University and Australian Government Department of Environment Water, Heritage and the Arts. Participants identified the need for a focussed treatment of the challenges in managing rivers and wetlands, given increasing effects of climate change and the widespread effects of other factors. I thank two anonymous referees for comments on a draft of this manuscript and Andrew Boulton for editorial oversight of this special issue and Leanne Hamilton for ongoing support.

References

Aldous, A., Fitzsimons, J., Richter, B., and Bach, L. (2011). Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research* **62**, 223–231. doi:10.1071/MF09285

Allan, J. D., and Flecker, A. S. (1993). Biodiversity conservation in running waters. *BioScience* **43**, 32–43. doi:10.2307/1312104

Arthington, A. H., Bunn, S. E., Poff, N. L., and Naiman, R. J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**, 1311–1318. doi:10.1890/1051-0761(2006)016[1311:TCOPEF]2.0.CO;2

Bates, B., Kundzewicz, Z. W., Wu, S., and Palutikof, J. (2008). Climate change and water. Technical paper of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change, Geneva. Available at http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf [accessed 15 February 2011].

Biggs, H. C., and Rogers, K. H. (2003). An adaptive system to link science, monitoring, and management in practice. In 'The Kruger Experience: Ecology and Management of Savanna Heterogeneity'. (Eds J. T. du Toit, K. H. Rogers and H. C. Biggs.) pp. 59–80. (Island Press: Washington, DC.)

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., *et al.* (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews of the Cambridge Philosophical Society* **81**, 163–182. doi:10.1017/S1464793105006950

Fitzsimons, J. A., and Robertson, H. A. (2005). Freshwater reserves in Australia: directions and challenges for the development of a comprehensive, adequate and representative system of protected areas. *Hydrobiologia* **552**, 87–97. doi:10.1007/S10750-005-1507-4

Gleick, P. H. (2003). Global freshwater resources: soft-path solutions for the 21st century. *Science* **302**, 1524–1528. doi:10.1126/SCIENCE.1089967

Gordon, L. J., Peterson, G. D., and Bennett, E. M. (2008). Agricultural modifications of hydrological flows create ecological surprises. *Trends in Ecology & Evolution* **23**, 211–219. doi:10.1016/J.TREE.2007.11.011

Hermoso, V., and Clavero, M. (2011). Threatening processes and conservation management of endemic freshwater fish in the Mediterranean basin: a review. *Marine and Freshwater Research* **62**, 244–254. doi:10.1071/MF09300

Herron, N., Davis, R., and Jones, R. (2002). The effects of large-scale afforestation and climate change on water allocation in the Macquarie River catchment, NSW, Australia. *Journal of Environmental Management* **65**, 369–381.

IPCC (2007). 'Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.' (Eds M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson.) (Cambridge University Press: Cambridge, UK.)

Kingsford, R. T., Boulton, A. J., and Puckridge, J. M. (1998). Challenges in managing dryland rivers crossing political boundaries: lessons from Cooper Creek and the Paroo River, central Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**, 361–378. doi:10.1002/(SICI)1099-0755(199805/06)8:3<361::AID-AQC294>3.0.CO;2-V

Kingsford, R. T., Brandis, K., Thomas, R. F., Crighton, P., Knowles, E., *et al.* (2004). Classifying landform at broad spatial scales: the distribution and conservation of wetlands in New South Wales, Australia. *Marine and Freshwater Research* **55**, 17–31. doi:10.1071/MF03075

Kingsford, R. T., Lemly, A. D., and Thompson, J. R. (2006). Impacts of dams, river management and diversions on desert rivers. In 'Ecology of Desert Rivers'. (Ed. R. T. Kingsford.) pp. 203–247. (Cambridge University Press: Cambridge, UK.)

Kingsford, R. T., Walker, K. F., Lester, R. E., Young, W. J., Fairweather, P. G., *et al.* (2011*a*). A Ramsar wetland in crisis – the Coorong, Lower Lakes and Murray Mouth, Australia. *Marine and Freshwater Research* **62**, 255–265. doi:10.1071/MF09315

Kingsford, R.T., Biggs, H.C., and Pollard, S.R. (2011*b*). Strategic adaptive management in freshwater protected areas and their rivers. *Biological Conservation*. doi:10.1016/J.BIOCON.2010.09.022

Klausmeyer, K. R., and Shaw, M. R. (2009). Climate change, habitat loss, protected areas and the climate adaptation potential of species in Mediterranean ecosystems worldwide. *PLoS ONE* **4**(7), e6392. doi:10.1371/JOURNAL.PONE.0006392

Lemly, D., Kingsford, R. T., and Thompson, J. R. (2000). Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management* **25**, 485–512. doi:10.1007/S002679910039

Lester, R. E., Webster, I. T., Fairweather, P. G., and Young, W. J. (2011). Linking water-resource models to ecosystem-response models to guide water-resource planning – an example from the Murray–Darling Basin, Australia. *Marine and Freshwater Research* **62**, 279–289. doi:10.1071/MF09298

MDBA (Murray–Darling Basin Authority) (2010). 'Guide to the Proposed Murray–Darling Basin Plan: Overview.' (Murray–Darling Basin Authority: Canberra.)

Millennium Ecosystem Assessment (2005). 'Ecosystems and Human Well-being: A Framework for Assessment.' (Island Press: Washington, DC.)

Milliman, J. D., Farnsworth, K. L., Jones, P. D., Xu, K. H., and Smith, L. C. (2008). Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change* **62**, 187–194. doi:10.1016/J.GLOPLACHA.2008.03.001

Milly, P. C. D., Dunne, K. A., and Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**, 347–350. doi:10.1038/NATURE04312

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Zbigniew, W., *et al.* (2008). Climate change – Stationarity is dead: whither water management? *Science* **319**, 573–574. doi:10.1126/SCIENCE.1151915

Milzow, C., Kgotlhang, L., Bauer-Gottwein, P., Meier, P., and Kinzelbach, W. (2009). Regional review: the hydrology of the Okavango Delta, Botswana – processes, data and modelling. *Hydrogeology Journal* **17**, 1297–1328. doi:10.1007/S10040-009-0436-0

Nel, J. L., Roux, D. J., Cowling, R. M., Abell, R., Ashton, P. J., *et al.* (2009). Progress and challenges in freshwater conservation planning. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19**, 474–485. doi:10.1002/AQC.1010

Nel, J. L., Turak, E., Linke, S., and Brown, C. (2011). Integration of environmental flow assessment and freshwater conservation planning: a new era in catchment management. *Marine and Freshwater Research* **62**, 290–299. doi:10.1071/MF09318

Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science* **308**, 405–408. doi:10.1126/SCIENCE.1107887

Palmer, M. A., Reidy Liermann, C. A., Nilsson, C., Flörke, M., Alcamo, J., *et al.* (2008). Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment* **6**, 81–89. doi:10.1890/060148

Palmer, M. A., Lettenmaier, D. P., Poff, N. L., Postel, S. L., Richter, B., *et al.* (2009). Climate change and river ecosystems: protection and adaptation options. *Environmental Management* **44**, 1053–1068. doi:10.1007/S00267-009-9329-1

Pittock, J., and Finlayson, C. M. (2011). Australia's Murray–Darling Basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research* **62**, 232–243. doi:10.1071/MF09319

Pittock, J., and Hartmann, J. (2011). Taking a second look: climate change, periodic relicensing and improved management of dams. *Marine and Freshwater Research* **62**, 312–320. doi:10.1071/MF09302

Poff, N. L., Allan, J. D., Palmer, M. A., Hart, D. D., Richter, B. D., *et al.* (2003). River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment* **1**, 298–306. doi:10.1890/1540-9295(2003)001[0298:RFAWWE]2.0.CO;2

Turak, E., Marchant, R., Barmuta, L. A., Davis, J., Choy, S., *et al.* (2011). River conservation in a changing world: invertebrate diversity and spatial prioritization in south-eastern coastal Australia. *Marine and Freshwater Research* **62**, 300–311. doi:10.1071/MF09297

Viers, J. H., and Rheinheimer, D. E. (2011). Freshwater conservation options for a changing climate in California's Sierra Nevada. *Marine and Freshwater Research* **62**, 266–278. doi:10.1071/MF09286

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288. doi:10.1126/SCIENCE.289.5477.284

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., *et al.* (2010). Global threats to human water security and river biodiversity. *Nature* **467**, 555–561. doi:10.1038/NATURE09440

Watts, R. J., Richter, B. D., Opperman, J. J., and Bowmer, K. H. (2011). Dam reoperation in an era of climate change. *Marine and Freshwater Research* **62**, 321–327. doi:10.1071/MF10047

Whalley, R. D. B., Price, J. N., Macdonald, M. J., and Berney, P. J. (2010). The impact of Lippia on the social-ecological systems of the Gwydir Wetlands and the Macquarie Marshes in northern NSW. In 'Proceedings of the 16th Biennial Conference of the Australian Rangeland Society, Bourke'. (Eds D. J. Eldridge and C. Waters.) (Australian Rangeland Society: Perth.) Available at http://www.austrangesoc.com.au/userfiles/file/2010_ARS_conf/Wal%20Whalley%20et%20al%20new.pdf [accessed 15 February 2011].

Manuscript received 6 February 2011, accepted 20 February 2011