Aquat Sci (2013) 75:73–93
DOI 10.1007/s00027-011-0232-5

Aquatic Sciences

EFFECTS OF CLIMATE CHANGE ON WETLANDS

The status of wetlands and the predicted effects of global climate change: the situation in Australia

C. M. Finlayson · J. A. Davis · P. A. Gell · R. T. Kingsford · K. A. Parton

Received: 29 November 2010 / Accepted: 6 August 2011 / Published online: 10 September 2011

Abstract The condition of many wetlands across Australia has deteriorated due to increased water regulation and the expansion and intensification of agriculture and increased urban and industrial expansion. Despite this situation, a comprehensive overview of the distribution and condition of wetlands across Australia is not available. Regional analyses exist and several exemplary mapping and monitoring exercises have been maintained to complement the more general information sets. It is expected that global climate change will exacerbate the pressures on inland wetlands, while sea level rises will adversely affect coastal wetlands. It is also expected that the exacerbation of these pressures will increase the potential for near-irreversible changes in the ecological state of some wetlands. Concerted institutional responses to such pressures have in the past proven difficult to sustain, although there is some evidence that a more balanced approach to water use and agriculture is being developed with the provision of increasing funds to purchase water for environmental flows being one example. We identify examples from around Australia that illustrate the impacts on wetlands of long-term climate change from palaeoecological records (south-eastern Australia); water allocation (Murray-Darling Basin); dryland salinisation (south-western Australia); and coastal salinisation (northern Australia). These are provided to illustrate both the extent of change in wetlands and the complexity of differentiating the specific effects of climate change. An appraisal of the main policy responses by government to climate change is provided as a basis for further considering the opportunities for mitigation and adaptation to climate change.

Keywords Climate change · Water regulation · Salinisation · Mitigation · Adaptation · Carbon emissions

This article belongs to the Special Issue "Effects of Climate Change on Wetlands".

C. M. Finlayson (✉)
Institute for Land, Water and Society,
Charles Sturt University, PO Box 789, Albury,
NSW 2640, Australia
e-mail: mfinlayson@csu.edu.au

J. A. Davis
School of Biological Sciences, Monash University,
Clayton, VIC 3800, Australia

P. A. Gell
Centre for Environmental Management, School of Science
and Engineering, University of Ballarat, PO Box 663,
Ballarat, VIC 3353, Australia

R. T. Kingsford
Australian Rivers and Wetland Centre,
University of New South Wales, Sydney, Australia

K. A. Parton
Institute for Land, Water and Society, Charles Sturt University,
PO Box 883, Orange, NSW 2800, Australia

Introduction

The ecological character of many wetlands across Australia has deteriorated in recent decades as a consequence of increased water regulation, the expansion and intensification of agriculture, and urban and industrial expansion (McComb and Lake 1988; Bunn et al. 1997; Finlayson and Rea 1999; Davis et al. 2010). Climate change and increased climate variability are expected to interact synergistically and cumulatively with existing drivers of change (e.g. changing land use and land cover, drainage, water diversions, and invasive species) to further complicate efforts to manage wetlands and maintain or restore their ecological character (Gitay et al. 2001; Pittock et al. 2001; Poff et al. 2002; Finlayson et al. 2006).

Given the extent of our current understanding of the existing drivers of change and their effects on wetlands, separating the effects of climate change will be difficult. Further, there is no comprehensive overview of the distribution and condition of wetlands across Australia. Regional analyses exist (Finlayson et al. 1997; Bunn et al. 1997; Kingsford et al. 2004a) and several exemplary mapping exercises have been developed, for example, that undertaken by the Queensland Wetland Program (Environmental Protection Agency 2005), but assessment and monitoring of wetlands is piecemeal. The importance of adopting a more strategic approach for monitoring and managing Australia's wetland resources has been shown by the adverse impacts of drought, coupled with heavy catchment disturbance, unprecedented elevations in salinity levels and acidification with no precedent, causing further wetland deterioration (Baldwin and Fraser 2009; Nielsen and Brock 2009; Davis et al. 2010).

Concerted institutional responses to the increasing pressures on wetlands have seldom been sustained, although there is evidence that Governments of the Murray-Darling Basin are redressing the imbalance between water use by irrigated agriculture and the environment through the purchase of environmental flows from the irrigation industry (Wong 2008). However, across Australia massive uncertainties related to the management of wetlands still exist, including the future challenge of adequately separating the impacts of climate change from those caused by other drivers of adverse change—the key issue explored in this paper.

Status of knowledge about wetlands and research activities

The status and knowledge of Australia's wetlands has increased in recent years with greater understanding of their distribution and extent, biota and ecological condition. There has been a considerable amount of research undertaken in Australian wetlands, although not evenly across the country. Research capacity is spread across many separately operating units, although there have been significant efforts to establish collaborative research efforts, such as the Cooperative Research Centre for Freshwater Ecology (http://www.ewater.canberra.edu.au/domino/html/Site-CRCFE/CRCFE_WebSite.nsf, accessed 3 October 2010) which undertook ecological research from 1995 to 2005 in order to improve and protect Australia's inland waterways. The Centre was succeeded in 2005 by eWATER which has focussed on the development and application of products for integrated water cycle management (http://www.ewater.com.au/about-us/, accessed 3 October 2010). The Queensland Wetlands Program is an ongoing program developed by the Australian and Queensland governments in 2003 with more than 30 projects that have delivered a range of new mapping, information and decision-making tools to support wetland managers and users to protect and manage wetlands (http://www.epa.qld.gov.au/UAT/wetlandinfo/site/WetlandInfobackground.html, accessed 3 October 2010).

Further national effort has occurred, but not necessarily through sustained programs. Land and Water Australia was established by the Australian Government in 1990 and continued until 2009. Its agenda included wetlands and rivers with several notable analyses, including an assessment of water needs for 2,746 wetlands along the River Murray (White et al. 2008). The National Land and Water Resources Audit was established in 1997 and continued until 2008 as a collaborative program between all States, Territories and the Australian Government to provide data, information, and nationwide assessments of Australia's natural resources. The second phase of the Audit included the development of information to support the assessment of change in natural resources as a result of government programs. It included an assessment of rivers and estuaries (Commonwealth of Australia 2002) using a macroinvertebrate and an environment index with four sub-indices (catchment disturbance, hydrological disturbance, habitat, and nutrient and suspended sediment load).

Recent research has, in particular, focussed on wetlands in the Murray-Darling Basin in the south-east of the country given drought conditions exacerbating ecological change caused by river regulation and water allocation policies. Research in the Basin has been undertaken by a number of institutions and agencies. A notable program includes the River Environmental Restoration Program coordinated by the New South Wales Department of Environment, Climate Change and Water (http://www.environment.nsw.gov.au/environmentalwater/rerp.htm, accessed 3 October 2010), which focussed on five major wetlands in the Basin. The Living Murray Initiative is an ongoing collaborative program between four governments that has focussed on achieving environmental benefits for six icon sites along the river (http://www.thelivingmurray2.mdbc.gov.au/; http://www.mdba.gov.au/programs/tlm, accessed 3 October 2010). It was established in 2002 in response to evidence showing the declining health of the River Murray system. From 2004–2009, it focussed on recovering 500 GL of water for the River Murray, specifically for the benefit of plants, animals and the millions of Australians it supports, along with improving the environment at the six icon sites.

A further substantial wetland program is being undertaken by the CSIRO Water for a Healthy Country (http://www.mdba.gov.au/programs/tlm, accessed 3 October 2010). A number of research institutions deal specifically with rivers and wetlands, namely the Australian Rivers Institute at Griffith University (http://www.griffith.edu.au/environment-planning-architecture/australian-rivers-institute, accessed 3 October 2010), the Australian Wetlands and Rivers Centre at the University of New South Wales (http://www.wetrivers.unsw.edu.au/index.html, accessed 3 October 2010), the Murray-Darling Freshwater Research Centre at Latrobe University (http://www.mdfrc.org.au/, accessed 3 October 2010), and the Australian Centre for Tropical Freshwater Research at James Cook University (http://www-public.jcu.edu.au/actfr/index.htm, accessed 3 October 2010). Many universities support wetland and river research through wider and more inter-disciplinary environmental research centres, including the Institute for Applied Ecology at Canberra University (http://www.appliedecology.edu.au/index.php#, accessed 3 October 2010), the Institute for Land, Water and Society at Charles Sturt University (http://www.csu.edu.au/research/ilws/, accessed 3 October 2010), and the Centre for Environmental Management at Ballarat University (http://www.ballarat.edu.au/ard/sci-eng/cem/, accessed 3 October 2010). A number of universities also support water research centres.

Possibly the most comprehensive wetland research and information program in recent years has been undertaken through the Queensland Wetland Program. The Australian Government's Department of Sustainability, Environment, Water, Population and Communities, and the Queensland Department of Environment and Resource Management are the lead agencies, with other government departments and key stakeholders also involved in the program's implementation. The project outputs include a report that scopes and documents the extent of research and corporate knowledge, and analyses gaps in knowledge on wetlands and the implications of these gaps on the ability of decision-makers and mangers to effectively undertake wetland protection and restoration (Conrick et al. 2007). The wetland inventory, classification and assessment program is possibly the best known outcome of this program. Other activities include the development of a meta-database and conceptual models of wetland types that can be used for research and management purposes.

The National Climate Change Adaptation Research Facility (http://www.nccarf.edu.au, accessed 3 October 2010) is a further collaborative program that was initiated in 2007 and includes a water resources and freshwater biodiversity research program and adaptation research network. The Australian Research Council Centre of Excellence for Climate System Science has recently been established at the University of New South Wales (http://www.ccrc.unsw.edu.au/index.html, accessed 3 October 2010).

Further national wetland research and assessment efforts include the national aerial waterbird surveys (Nebel et al. 2007; Kingsford et al. 2008), the national river health assessment (Commonwealth of Australia 2002), and the tropical rivers inventory and assessment project (Lukacs and Finlayson 2010; Bartolo et al. 2008; de Groot et al. 2008). The latter was undertaken by the National Centre for Tropical Wetland Research (http://www.environment.gov.au/ssd/nctwr.html, accessed 3 October 2010) which was disbanded after the commencement of the Tropical Rivers and Coastal Knowledge program in 2005. Lukacs and Finlayson (2010) brought together information from the Tropical Rivers Inventory and assessment Program and also from the Southern Gulf Environmental Information Program and the National Wetlands Research and Development Scoping Review.

Distribution and extent of wetlands

Australia contains an array of wetland types, but despite the history of wetland loss and degradation, the distribution and area of wetland types across Australia is not evenly documented and mapped and a national wetland inventory does not exist. An overview of wetland types in Australia and their ecological features is provided by Finlayson and von Oertzen (1993) and Jacobs and Brock (1993).

There have been many other mapping and inventory efforts, but often at different scales and with different definitions of wetlands (Spiers and Finlayson 1999). A national directory of important wetlands is available (http://www.environment.gov.au/water/topics/wetlands/database/diwa.html) and provides a substantial knowledge base. It was coordinated by the Australian Government and was first published in 1993 with the cooperation of conservation agencies and resource managers in all States and Territories. While the Directory constitutes a long-running information collation exercise, it is incomplete; it contains information on 904 inland, coastal and marine wetlands covering 57,904,254 ha (Table 1).

While a coordinated approach to wetland inventory has not been achieved (Spiers and Finlayson 1999) the Queensland and Australian governments have collaborated in the Queensland Wetland Program that has produced a comprehensive inventory, classification and mapping of 18.9 million ha of wetlands across the State (Environmental Protection Agency 2005; http://www.epa.qld.gov.au/UAT/wetlandinfo/site/WetlandInfobackground.html). The Queensland program could provide a model for a coordinated national approach to wetland inventory, assessment and monitoring.

Table 1 Number of wetlands and their approximate area (ha) across the States and Territories of Australia (data from The Directory of Important Wetlands of Australia 1996 and 2005; http://www.environment.gov.au/water/topics/wetlands/database/diwa.html; accessed 12 January 2010)

Jurisdiction	1996		2005	
	Number	Area	Number	Area
Australian capital Territory	13	670	13	1,257
New South Wales	94	2,171,740	187	2,340,815
Northern Territory	30	2,912,790	33	4,033,230
Queensland	165	11,453,560	210	42,964,286
South Australia	68	4,100,290	84	4,225,387
Tasmania	91	20,830	89	51,514
Victoria	121	395,100	159	557,888
Western Australia	110	2,056,250	120	2,583,325
External Territories	6	1,090,580	9	1,146,552
Total	688	24,201,810	904	57,904,254

Mapping the distribution and area of waterbodies (wetlands) in each of the major drainage basins in Australia has also been undertaken by Geoscience Australia at a scale of 1:250,000 (Table 2). These data were derived from paper maps which used aerial photography. The relative accuracy of the estimates derived from the map was checked against separate mapping of wetlands in the Murray-Darling Basin—this provided an estimate of 5,677,600 ha (Kingsford et al. 2004a) or 6% higher than the 5,341,700 ha from the Geoscience Australia data. The maps covered an estimated 23,007,700 ha of natural wetland and an additional 665,700 ha of man-made wetlands across Australia with about half of the wetlands classed as floodplains and about a third classed as lakes. Four river basins stand out as having most (87%) of the wetland area (Table 2): the Lake Eyre Basin (31%), the Murray-Darling Basin (23%), Timor Sea (18%) and Gulf of Carpentaria (15%).

The overall area of wetland derived from the mapping data was only 40% of the area of wetlands listed in the Directory (Table 1). There are several identified reasons for this difference. The Directory includes marine wetlands (e.g. Great Barrier Reef, 34,108,876 ha). Also, large discrepancies can occur between estimates of wetland area derived from maps; for example, estimates varied considerably for the wet-dry tropics of northern Australia (0–9,870,300 ha) depending on the mapping data used

Table 2 Locations and area (ha) of major wetland types in Australia, based on the GeoScience Australia 1:250,000 waterbody data layer

Basin	Total natural wetlands[a]	Lakes	Floodplains[b]	Swamps	Marine wetlands[c]	Rivers[d]	Man made wetlands[e]
1. North East Coast	9,813.80 (4)	469.76	3,224.65	1,140.37	3,221.78	1,757.24	1,132.93
2. South East Coast	7,222.36 (3)	2,588.56	2,438.47	870.64	842.63	482.06	696.95
3. Tasmania	1,724.83 (1)	364.11	100.62	540.60	480.97	238.53	1,199.60
4. Murray-Darling Basin	53,416.56 (23)	10,066.29	39,500.09	2,985.75	16.07	848.38	1,996.23
5. South Australian Gulf	7,542.77 (3)	5,860.36	465.57	13.79	1,177.67	25.38	98.69
6. South West Coast	11,965.06 (5)	6,141.72	5,138.29	437.62	79.81	167.61	115.26
7. Indian Ocean	17,089.32 (7)	3,693.70	4,824.89	97.87	3493.25	4,979.60	115.27
8. Timor Sea	42,406.43 (18)	737.51	23,526.56	2,669.56	11,925.26	3,547.54	1,101.17
9. Gulf of Carpentaria	34,838.10 (15)	648.44	22,256.51	1,725.69	7,362.34	2,845.11	128.10
10. Lake Eyre Basin	72,212.60 (31)	25,292.04	43,686.57	1,334.01	0.00	1,899.98	18.90
11. Bulloo-Bancannia	9,436.04 (4)	607.58	7,696.99	1,121.02	0.00	10.45	8.49
12. Western Plateau	53,576.15 (23)	44,116.12	7,856.14	241.39	448.09	914.41	46.22
Total	23,3077.84	75,095.41	109,847.67	7,189.54	23,228.94	17,716.29	6,657.79
% of types	n.a.	31.3	45.8	3.0	9.7	7.4	2.8

n.a. not applicable

[a] Includes lakes, floodplains, swamps, watercourses, rapids and marine wetlands

[b] Areas subject to inundation

[c] Saline coastal flats, foreshore flats and marine swamps

[d] Watercourses and rapids

[e] Canals, salt evaporation basins, aquaculture, flood irrigation storage, settling ponds and town rural storages

(Lowry and Finlayson 2004). These problems make it difficult to provide an explicit spatial analysis of climate change on wetlands across the continent, but a general analysis is possible.

There are 64 wetlands covering 7,509,830 ha also listed as Internationally Important under the Ramsar Convention on Wetlands, representing 7% of the wetland sites and 13% of the total area of wetlands listed in the Directory.

Climate change and wetlands

By 2030, temperatures over Australia are projected to rise by about 1°C with smaller increases in coastal areas and larger increases inland (CSIRO and Australian Bureau of Meteorology 2007). If greenhouse emissions are low, temperatures of 1–2.5°C are likely around the year 2070, and 2.2–5.5°C under higher emissions. There will also be changes in temperature extremes, with fewer frosts and substantially more days over 35°C than currently (CSIRO and Australian Bureau of Meteorology 2007).

As well, annual average rainfall is predicted to decrease by 2030 in southern Australia and remain stable in the far north (CSIRO and Australian Bureau of Meteorology 2007). Later projections in the century are more dependent on greenhouse gas emissions. Under a low emission scenario in 2070, rainfall is expected to decrease by 7.5% and under a high emission scenario decrease by 10%. There will be more dry days, although it is likely to be more intense when it does rain.

Other findings from the CSIRO and Australian Bureau of Meteorology (2007) report include: (1) droughts becoming more frequent, particularly in the south-west; (2) evaporation rates increasing, particularly in the north and east; (3) high-fire-danger weather increasing in the south-east; (4) tropical cyclones becoming more intense; and (5) sea levels continuing to rise. Downscaled projections are being developed across Australia to more accurately predict rainfall, allowing the development of adaptation and policy responses by individuals and agencies. For wetlands, much attention is directed towards climate scenarios for the Murray-Darling Basin in the south-east where drought conditions have exacerbated water management issues and led to the degradation of many wetlands (Baldwin and Fraser 2009; Nielsen and Brock 2009; Pittock and Finlayson 2011).

Climate change is predicted to result in changes in the ecological character of wetlands through increased temperatures and changes in precipitation. It will though be difficult to differentiate the impacts of climate change from other impacts, given the current condition of many important wetlands. This has relevance to the Ramsar Convention on Wetlands. Australia, as a Contracting Party to the Convention, is required to report to the Convention any changes in the ecological character of wetlands listed as Internationally Important. The Australian Government has determined that change due to climate change will not be reported because of its pervasiveness (Department of the Environment, Water, Heritage and the Arts 2009). The practicality of this policy is open to question as it implies that Australian officials can differentiate between the effects of climate change and other drivers of change (Pittock et al. 2010). It is contended that this will be a difficult exercise, especially without further information on the cumulative and synergistic interactions between drivers of change, including climate change.

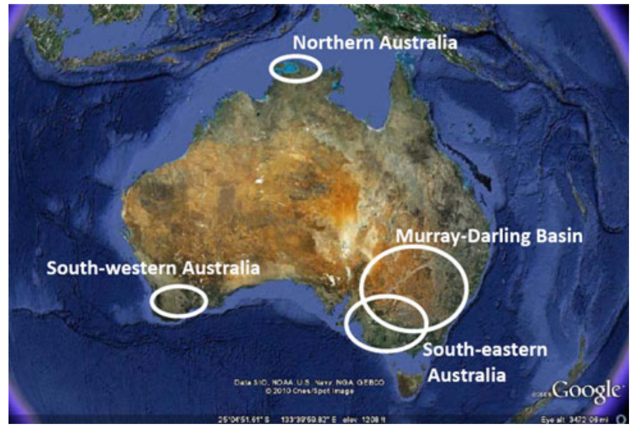

Fig. 1 Generalised location of wetland study areas

In support of this contention, we identify examples from around Australia (Fig. 1) that illustrate the impacts on wetlands of long-term climate change from palaeoecological records (south-eastern Australia); water allocation (Murray-Darling Basin); dryland salinisation (south-western Australia); and coastal salinisation (coastal wetlands in northern Australia). A systematic analysis of impacts on all Australian wetlands is not provided. These examples are provided to illustrate both the extent of change in wetlands and the complexity of differentiating the specific effects of climate change. An appraisal of the main policy responses by government to climate change is provided as a basis for further considering the opportunities for mitigation and adaptation to climate change. These are currently focused on reducing carbon emissions, although an adaptation program is being developed (Palutikof 2010).

Climate change—long-term changes in south-eastern Australia

The same forces that have influenced the global climate over the long-term have changed the nature of wetlands in Australia. Over the last interglacial cycle, wetlands were

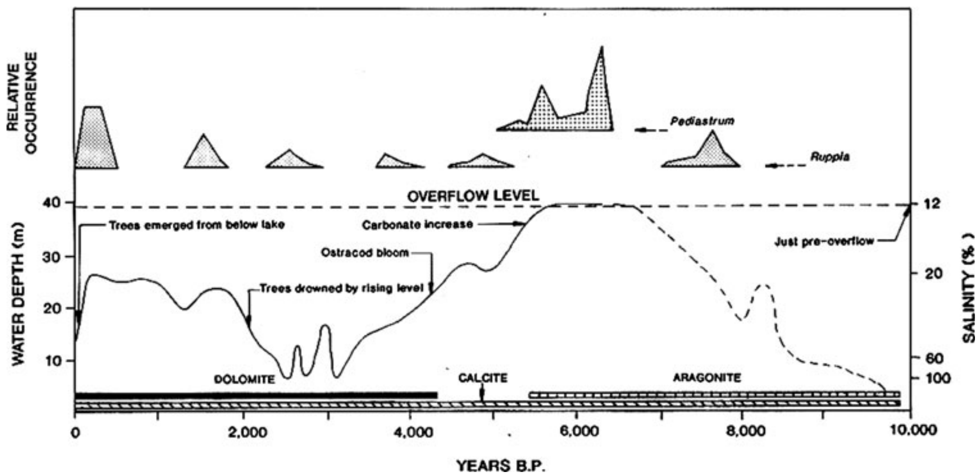

Fig. 2 Inferred level of Lake Keilambete through the Holocene (from Bowler 1986)

ever changing, with even the present day playa, Lake Eyre, full and relatively fresh for long periods with a positive rainfall balance augmented by drainage from a vast catchment (Magee et al. 1995). During the last glacial maximum (18,000 years ago), rainfall was as little as 50% present day values and many south-east Australian wetlands were dry—a time of particular stress for Australia's aquatic biota (De Deckker 1986). Some deep, crater lakes persisted, but there was probably a considerable diversity bottleneck. For example, Brachina Gorge, presently a creek line in an incised arid zone gorge, supported a substantial wetland between 40,000 and 13,000 years ago through groundwater supply and low evaporation (Williams et al. 2001). Monsoon rain on a denuded catchment probably breached the natural impoundment to this wetland and with increasing temperatures reduced effective rainfall (Williams et al. 2001).

Climate change over the last 10,000 years of the Holocene is possibly the most relevant to future climate change. The deep crater lakes in south-eastern Australia remained wet and shallow, leading to the warmer and wetter epoch when they all filled by 7,000 years ago. The reliability of high discharges in the main rivers of the Murray-Darling Basin began to diminish, resulting in deposition of the Monomon Formation across a wide floodplain, overlain with the clay-rich Coonambidgel Formation from the most humid phase. Lake Keilambete illustrates this rainfall history through the salinity record (Bowler 1986), while nearby large crater lakes overflowed between 7,000 and 5,500 years ago, reflecting the strong positive rainfall balance (Gell et al. 1994; Chivas et al. 1986; Gell 1998; Fig. 2). There was then an extended drying phase from 5,000 years ago, with lake levels as low and variable as today for 2–3,000 years. Low lake levels in Lake Keilambete have exposed trees aged by radiocarbon dating to ca. 2,200 years ago; the lake has varied in depth from 28 m deep in 1859 to only 8 m deep today (Jones et al. 1993). Similarly, Lake Bullenmerri dried (Jones et al. 2001). Climate-lake level response modelling poses the prospect that this lake level decline was driven by a 15% decline in rainfall or increase in evaporation, or more likely a combination of the two. The variability in the rainfall record suggests that temperature driven increases in evaporation is the principal force. The start of this climatic shift has remained uncertain owing to the challenges in dating the temporal blind spot between the youngest radiocarbon, and oldest ^{210}Pb ages that have been determined. Despite this, recent evidence is for an extended period of drying commencing as much as 600 years ago (P. De Deckker, personal communication). The instrumental record shows strong variability through the period of European settlement under the influence of the multi-decadal oscillation. The recent extended drought, the driver of much recent interest in climate change in Australia, is likely a symptom of this longer term variability, although elevated global temperatures are likely to have played a major role in the regional water balance.

Outside the crater lakes, the centre of considerable climate change research focus over decades, few wetlands reveal evidence for the impact of the 'Keilambete' record of climate change and variability. Coastal wetlands are driven by the influence of geomorphic maturation and changing marine connection (sensu Roy 1984) and their responsiveness to changing effective rainfall is unclear. Floodplain wetlands, like their estuarine counterparts, pose challenges in the establishment of a clear geochronology. Their records of response to climate are also mediated by the size of the catchment and effect of vegetation cover, itself affected by effective rainfall on catchment efficiency (e.g. Schumm 1968). Nevertheless, a diatom record from the River Murray floodplain attests to fresh lagoonal conditions at the height of the mid-Holocene pluvial (Gell et al. 2005a), replaced by heightened river activity, or connectivity, until ca. 3,000 years ago. So, the rainfall surplus responsible for filling Lake Keilambete to the point of overflowing appears to have extended 400 km inland. The subsequent drying phase may also have extended regionally and increased the water shedding capacity to drive channel migration or more regular overbank flow. Whichever explanation proves true, this wetland at least, appears to have been quite responsive to the shifts in climate well documented from the crater lake sediment records.

At the mouth of the River Murray, despite ongoing geomorphic development after the marine transgression, is a sediment record of remarkable stability through the 7,000 years before the arrival of European settlement (Fluin et al. 2007). Both the sediment and diatom records of the lower lakes and tidal coastal lagoon, the Coorong, reveal little change through this extended period. While the lack of resolution denies access to a record of response to climatic variability over this time, it is clear that this wetland, at this time scale, was resilient to the shifts in effective rainfall and runoff evident at Lake Keilambete and Tareena Billabong, respectively.

An array of records of wetland change now exists for the period spanning the arrival of European settlers to the continent. These have been integrated under a national research network aimed at identifying the relative influence of human driven ecosystem change relative to century scale climate change and variability (Fitzsimmons et al. 2008). Prior to European settlement, most wetlands were shown to be relatively stable in terms of fossil, diatom-inferred condition. Many River Murray wetlands were relatively clear and supported aquatic macrophytes (Reid et al. 2007). Some lowland sites were circum-neutral (Gell et al. 2005b), to even slightly acid (MacGregor et al. 2005), before European settlement. Some lakes, in some contexts, attest to a saline past (Gell et al. 2007a), however, again the lack of resolution precludes interpretation in terms of extent and periodicity, and so cause. Outside the climatically sensitive crater lakes however, none provide clear evidence for the recent phase of desiccation that has prevailed over recent centuries.

In part this lack of a clear, century-scale record of change and variability is on account of the early, and substantial, impact of catchment development on many wetlands. Catchment surfaces are known to have become mobilised very early in settlement, and, while these subsequent, high sedimentation rates compromise the ^{210}Pb-dervied chronologies for this time period, the best dated sequences suggest that the response to catchment development was almost immediate (Gale and Haworth 2005). The more sensitive, up-catchment wetlands reacted to this increased flux of sediments through increased turbidity that impacted the light dynamics and drove the replacement of productive macrophyte-rich systems to a phytoplankton-dominated state (Ogden 2000; Reid et al. 2007). Lower down the River Murray, particularly near major stock routes, sedimentation rates increased from the mid-to-late 1800s. Here, sediment infilling rates increased 30-fold. While they are shown to decline after regulation in the 1920s owing to improved sediment trapping in the main channel (Olley and Wallbrink 2004), rates have increased in recent decades in several wetlands in the lower parts of the Basin (Gell et al. 2009). Here, the rapid infilling of shallow wetlands raises the prospects of complete wetland loss within decades in some cases (Gell et al. 2006).

This period of European settlement has witnessed a sequence of substantial floods and droughts. Despite aforementioned issues of temporal resolution, wetland sediment records appear to be continuous and changes appear to be incremental rather than episodic. There is no clear evidence of the one-in-a-century 1956–1958 flood associated with an extended period of positive Southern Oscillation Index values, nor the lesser River Murray floods of 1870 or 1917. Nor is there evidence of the oscillating drought and flood-dominated periods (Vivès and Jones 2005) that have driven effective rainfall and runoff at multi-decadal, scales. There is clear evidence, in most floodplain wetlands however, of the elevation of river height behind the weirs built from 1922–1940, in terms of a sustained increase in phytoplankton relative to benthic diatom taxa. So, at least as determined by these algal bioindicators, these wetlands have been relatively resilient to hydrologic extremes driven by regular climate events, but relatively sensitive to direct changes to the prevailing hydrological condition.

Lake salinity is used as a proxy for water balance in the ‘rain gauge’ lakes and these have passed through tenfold shifts in salinity due to changing climates over millennia. In larger catchments, this simple model is complicated by the more distant and variable source of salts and the impact of groundwater (Torgersen et al. 1986). Sustained increases in salinity are evident as early as 1880 AD (Gell et al. 2005a) and elsewhere through the 1900s (Gell and Little 2006; Gell et al. 2009). Some sites, hitherto considered in good ecological condition, have been shown to be between 5–10 times more saline that before settlement (Gell et al. 2007a). The unprecedented entry of certain, salt tolerant river plankton, into the record at several sites, may reveal recent increases in river salinity, although this is inconsistent with the instrumental record which reveals relatively steady river salinity values since the 1950s. The tolerance of this species, *Actinocyclus normanii*, to elevated nutrient concentrations, as well as salt, may reveal the recent, unprecedented shift to more saline, and eutrophic, river waters. Certainly the records of lentic taxa within wetlands suggest an increase in turbidity, salinity and nutrients, from the 1800s, particularly after regulation, and, in places, increasing to the present. Interestingly, these shifts in water quality are coincident in several records leading to suggestions that the drivers and stressors of wetland condition co-vary to a degree (Gell et al. 2007a), potentially due to the interrelationship between erosion and nutrient release, salinity, sodicity and erosion, and eutrophication and turbidity. All wetlands examined have departed from their respective 'range of natural variability' as defined by their pre-European condition.

Recently, exceptionally dry conditions have combined with these drivers of catchment change to generate conditions unprecedented in the records of some wetlands. Those subjected to artificially maintained water levels tied to the lock systems have accumulated sediments and salts over the last 60 years. Due to the gypseous nature of the landscape in the lower basin, sulphate salts have been leached and released into the waterways, to accumulate in sediment sequences. The permanently maintained weir pools have precluded exposure to oxygen, inducing reduction of sulphates to sulphides. Low flows from abstraction and prolonged drought have eliminated inflows exposing pools to evaporation loss and drawdown. Exposure of sulphides has led to oxidation and acidification despite the strong buffering effect of the limestone landscape. Several wetlands closely associated with weir pools are now suffering acidification from pH values around 9 to 5 or less. At the end of the River Murray, Lake Albert is at risk of acidification (Fitzpatrick et al. 2008) and managers have been drawing water from the nearby Lake Alexandrina to control oxidation of sulphides.

The record from the crater lakes suggests that south-east Australia has been experiencing a long-term drying trend for several centuries. The instrumental records attests to an increase in mean Australian surface temperature of 0.9°C since 1910, with most of the increase from the 1950s (Cai et al. 2007). The record of precipitation has been much more variable. An extended dry period prevailed in eastern Australia between the mid 1890s and late 1940s. This was followed by a wetter period bracketing the La Niña events of 1956 and 1974. An abrupt decrease in rainfall commenced in the late 1960 in south-west Western Australia and from the late 1970s in the east, associated with an extended period of negative SOI values. A further decline in rainfall across south-eastern and eastern Australia, commencing in 1997 (Hennessy et al. 2007), was accompanied by an abrupt increase in maximum temperatures.

These current extreme dry conditions have brought to the fore the environmental and social risks associated with climate change. Many scenarios of climate futures have been generated for Australia since the mid-1980s (Pittock and Nix 1986; Pittock et al. 2001) and more recently for the Murray-Darling Basin. Only in recent years have mangers come to understand the degree to which climate change has and will influence decisions about allocations of water for consumptive and environmental purposes. Now, with most lakes in south-east Australia having been dry, or at record low levels, the issue of water resource availability under a drying future has become acute.

Scenarios of climate change through the 21st Century flag the present conditions as increasingly likely, and normal to wet years as less likely. Scenarios of higher temperatures place wetlands at heightened risk owing to increased evaporation. Greater thermal energy is driving winter westerly systems southward leading to increased risk of reduced wet season rainfall in the south, by as much as 13.1% (Giorgi 2006). In combination, increased temperatures and reduced winter rainfall generate scenarios of 5–25% decline in flow to all southern Murray-Darling Basin rivers (Fig. 3; Jones et al. 2002). These are the most hydrologically productive, compounding the risk of low flow scenarios into the future. A combined temperature and rainfall model raises the prospect for runoff reductions of up to 50%, such as under the not so unlikely prospect of a 2°C increase in temperature combined with a 13% decline in rainfall. While reduced rainfall will lower saline water tables, reduced flow is likely to generate decreased water quality in terms of salinity (Fig. 4; Jones and Durack 2005), but also potentially turbidity and eutrophication due to reduced flushing. The ephemeral nature of inland waters will continue as higher temperatures will have limited impact on regions that are already macrothermic. The potential for summer flooding, however, is heightened with increased temperatures increasing monsoonal penetration further into the continent. This activity has filled Lake Eyre in the past and it remains possible that amplification of flows in such a large catchment extending into the tropics may trigger more frequent infilling events.

The availability of surface water for consumptive and environmental use is greatly contested in southern and eastern Australia. Scenarios for increased temperatures, reduced wet season rainfall, reduced runoff and declining stream water quality suggest that the allocation of these resources will be even more acute into the future. The record of wetland change across south-eastern Australia, however, suggests that changing river flow is only one of the drivers of degradation. The allocation of scarce, and increasingly costly, freshwater under environmental flow programs, is unlikely to restore floodplain wetlands that have suffered salinisation, eutrophication, accelerated sediment infilling and/or acidification. The provision of freshwater would be most effective, and perhaps best received by the community, if allocated to wetlands where the effects of these stressors have been mitigated.

Palaeoenvironmental records of the changing conditions of wetlands are largely focussed to the south-east owing to the concentration of research centres and the more humid

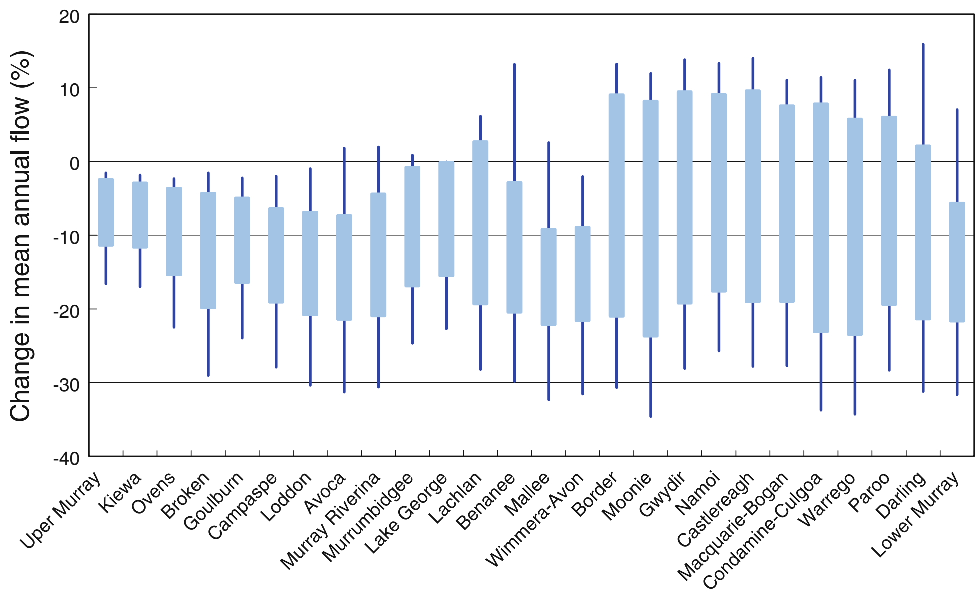

Fig. 3 Modelled flow reductions across sub-catchments of the Murray-Darling Basin (Jones et al. 2002)

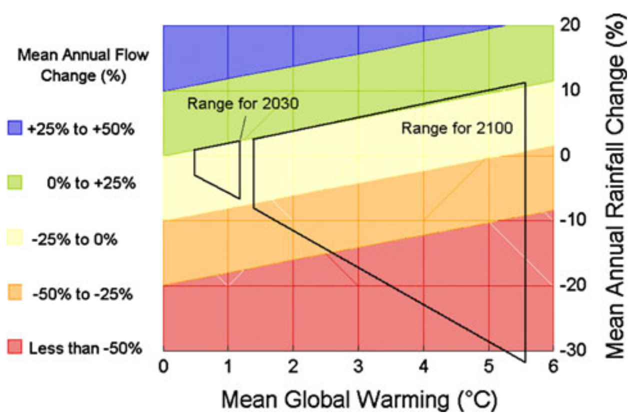

Fig. 4 Murray-Darling Basin runoff response to warming and rainfall change (Gell et al. 2007b)

conditions allowing for the preservation of suitable records. The crater lakes in the region have been shown to be sensitive to changing water balance, have falling lake levels, and are likely to fall in the future. Some riverine wetlands have changed over millennial timescales in ways consistent with these records of change from the crater lakes. Others have been shown to be resilient to the amplitude of changes witnessed through the Holocene, although greater resolution sampling may reveal a certain degree of responsiveness. Since European settlement, catchment development on a large scale has driven substantial and sometimes unprecedented changes to wetland condition. River regulation has provided the environmental conditions that, in coastal contexts, typically take millennia to develop. The recent extreme drought conditions have combined to generate acidification episodes that are outside the experience of these wetlands. Climate scenarios flag the risk of ongoing drying in the south, compounding the impact of regulation, abstraction and catchment development.

Climate change—water allocation in the Murray-Darling Basin

The Murray-Darling Basin is Australia's largest river basin and comprises a part of south-eastern Australia which has high agricultural and biodiversity values (ABS et al. 2009). It covers 1,061,500 km^2 or 14% of the land area of Australia with the River Murray extending 2,530 km, the Darling 2,740 km and the Murrumbidgee, a tributary of the Murray, 1,690 km (Fig. 5; CSIRO 2008). The environment of the Basin ranges from high rainfall alpine districts in the east, which account for 5% of the area and contribute over 50% of the runoff to the River Murray, to the vast semi-arid grass and woodlands which comprise most of the area of the Basin (CSIRO 2008).

The rivers of the Murray-Darling Basin have been greatly affected by the building of dams and the diversion of water from rivers—the Basin has more dams, storage capacity and water diversions than any other large river basin in Australia (Table 3). The 248 large dams in the Basin have a total storage capacity of 29,907,795 ML, which represents 125% of the mean annual runoff with 66% of this being diverted, largely for irrigation purposes.

While the data for large storages provide a useful index of the change that has occurred in river basins, it does not adequately capture the many hundreds of privately constructed storages in the lower parts of river systems, particularly on the floodplains of the Murray-Darling Basin. Those used for the capture of variable flows on the inland rivers can hold considerable quantities of water. Most occur in the Darling River catchment (Kingsford

Fig. 5 Murray-Darling Basin, south eastern Australia

2006). The largest known private storages in the Basin (~380,000 ML) occur on the Condamine-Culgoa catchment in the north (Kingsford 2000b).

Our knowledge of the distribution of earthworks (levees and channels) on floodplains that affect flows to floodplain wetlands is poor. The role of earthworks in interrupting or denying flows to parts of the floodplain is not well-recognised. We know of only one comprehensive analysis of a floodplain's earthworks: the Macquarie River floodplain where there were more than 2,100 km of earthworks, potentially interrupting flows across the floodplain and disconnecting vegetation on the floodplain from the river (Steinfeld and Kingsford 2008). Other river management structures (e.g. small weirs) may also affect flows to wetland systems. Some large lakes (e.g. Menindee Lakes, Lake Victoria) on some of the major rivers in the Murray-Darling Basin were converted to reregulating storages by building dams and structures that held the water of the lakes in storage. These have often resulted in the imposition of a flow regime that is now more perennial than annual (Kingsford et al. 2004b).

Nearly all major river systems in the Murray-Darling Basin are affected by reduced flows, sometimes exceeding 50% of their natural flows (Kingsford and Thomas 1995; Maheshwari et al. 1995; Thoms and Sheldon 2000; Kingsford and Thomas 2004). The median annual flow of the Murray-Darling Basin to the Southern Ocean is 28% of natural levels (Goss 2003). This decreased flow translates into reduced overbank flows to floodplain wetlands, affecting the biodiversity and traditional pastoralism that

Table 3 Locations number and total storage capacity of large storages in river basins in Australia

River basin	Land area ($km^{2)}$	Mean annual runoff[a] (ML)	No. of storages	Total storage capacity (ML)	Storage capacity as % of mean annual runoff	Diversions (ML)[b]
North-east Coast	450,700	73,411,000	143	9,679,921	13.2	3,182,000 (17.5%)
South-east Coast	273,600	42,390,000	188	14,598,613	34.4	1,825,000 (10.1%)
Tasmania	68,200	42,582,000	123	28,951,882	68.0	451,700 (2.5%)
Murray-Darling	1,062,530	23,850,000	248	29,907,795	125.4	12,051,000 (66.4%)
South Australian Gulf	82,300	952,000	40	380,757	40.0	144,000 (<1%)
South-west Coast	314,090	6,785,000	55	1,039,176	15.3	373,000 (2.1%)
Indian Ocean	518,570	4,609,000	3	96,255	20.9	12,000 (<1%)
Timor Sea	547,050	83,320,000	17	6,590,524	7.9	48,000 (<1%)
Gulf of Carpentaria	638,460	95,615,000	12	341,610	0.4	52,000 (<1%)
Lake Eyre	1,170,000	8,638,000	8	31,805	0.4	7,000 (<1%)
Bulloo-Bancannia	100,570	546,00	0	0	0	<1 (<1%)
Western Plateau	2,455,000	1,486,000	9	305	0.02	1,000
Total	7,679,280	387,184,000	846	91,618,643	23.7	18,147,000

Mean annual runoff based on 1983/1984 data, published in AWRC (1975). Numbers of storages and total storage capacity data from GeoScience for registered dams. Diversion data from NLWRA (2001a)

[a] Outflow from basins where flow is greatest at the mouth of the river basin or combined mean annual runoff at points where flow is greatest in each major catchment of a river basin, excluding runoff from upstream basins (AWRC 1975)

[b] Data from NLWRA (2001a) with percentages in each of the river basins

relies on flooding. The reduction in flows to wetlands is the major driver affecting ecosystems and their dependent organisms (Kingsford 2000a). River regulation, diversion of water and earthworks all reduce the connectivity of floodplain wetlands and their dependent organisms to the river.

It is not surprising that the floodplains and wetlands of the Murray-Darling Basin are most affected by water resource development, given the relatively high number of storages and diversions. Many of its major wetlands are in serious ecological decline (Kingsford 2000a; Arthington and Pusey 2003; Kingsford et al. 2006). The most obvious impacts are changes and contractions in perennial vegetation communities (Bren 1992). Floodplain eucalypts tolerant of less frequent flooding are invading areas that were frequently flooded (e.g. the Barmah–Millewa Forest; Bren 1992). Some floodplain eucalypt communities have died or are severely in decline on the lower River Murray, as a result of decreases in the frequency and extent of inundation and less flushing of saline soils (Jolly et al. 1993; MDBC 2003). The ecological impacts extend to all dependent organisms and ecological processes.

Foodweb processes are also considerably reduced. Water resource development has reduced the amounts of dissolved organic carbon released onto the floodplain of the Condamine-Balonne in the northern Murray-Darling Basin by about 5,000 tonnes (Thoms et al. 2006). Invertebrate communities adapted to flooding and drying exhibit major declines in density and species richness, as the time between floods increases (Boulton and Lloyd 1991). With river regulation, fish communities have become increasingly dominated by exotic species (Gehrke et al. 1995), sometimes even exceeding 80% (Gehrke and Harris 2001). Spectacular declines in waterbird communities have occurred on floodplain wetlands where the frequency and extent of flooding has declined (Kingsford and Thomas 1995, 2004). This has probably affected the potential for colonially breeding waterbirds to recruit on key wetlands in the Murray-Darling Basin (Kingsford and Johnson 1998; Leslie 2001). For lakes that are used as storage and with water levels that are kept artificially high, there is a decline in species diversity, reflected in significant changes to the waterbird community in these lakes compared to naturally flooding lakes (Kingsford et al. 2004b). Relatively little is known of the effects of altered flow regimes on other organisms, although small terrestrial mammals may decline where floods are reduced (Lada et al. 2007, 2008).

Knowledge of these serious ecological effects is driving a major policy initiative within the Murray-Darling Basin to rehabilitate the rivers. This began when an expert panel recommended that for a moderate chance of ecological recovery, the River Murray required 1,500,000 ML of water. The Australian and State Governments adopted a policy position of returning 500,000 ML to the river. Currently the governments are committed to expenditure of about \$A9 billion, of which \$3.1 billion is dedicated to the buy-back of water from irrigation licences to reallocate to the environment. The rest of the money is improving the efficiencies of irrigation so that water can be returned to rivers. The increasing quantum of environmental flows will place considerable pressures on governments to adequately manage the environmental flows for good environmental outcomes.

The above-mentioned changes are all attributed to changes in the water regime of the Basin as a consequence of the construction of dams and diversion of water away from the rivers and wetlands. These changes have impacted the ecological character of the wetlands through the combined and multiple effects of reduced and aseasonal flows. At the same time, many wetlands have been impacted by the spread of invasive species (e.g. C*yprinus carpio*; Koehn 2004), salinisation (Nielsen and Brock 2009) and by the addition of nutrients, whether from diffuse or point sources (MDBMC 1994). Whilst efforts are underway to better describe the ecological character of Ramsar wetlands in the Basin (http://www.environment.gov.au/water/policy-programs/wetlands/rampp.html, accessed 24 January 2010), they are under increased pressure from drought conditions (Lake 2008) and the inter-related impact of acidification (Baldwin and Fraser 2009) which may cause fundamental and irreversible changes in their character.

As reduced rainfall and extended droughts are projected under climate change scenarios the current conditions may come to represent the future—a future of increased temperatures and evaporation and drier or less frequently flooded wetlands. Given the above mentioned consequences for rivers and wetlands from water regulation across the Basin, it may be difficult to ascertain whether the changing climate or past and future water regulation are the primary cause of adverse change in the wetlands. Given our current understanding of the ecological impacts of dams and diversions in the Murray-Darling Basin, similar effects will be likely under reduced rainfall. The above discussion has focussed on wetlands within the Basin, but the impact of reduced flows will also affect estuarine wetlands and nearby marine ecosystems (Gillanders and Kingsford 2002). The ecological condition of the Coorong and Lakes Alexandrina and Albert wetland at the mouth of the River Murray has attracted a lot of attention given the perilous situation with low water levels and acidification (Kingsford et al. 2009; Phillips and Muller 2006). Without further large flows of fresh water, the condition of these wetlands is likely to deteriorate further—further flows are dependent on water policy allocation and further rainfall across a drought-affected catchment.

Climate change—dryland salinisation in south-western Australia

The south west of Australia covers an area of 140,000 km^2 with large tracts of land cleared of native vegetation and replaced with agriculture since European settlement some 180 years ago. The climate grades from cool, wet winters and hot, dry summers in the southwest to semi-arid and arid inland. Much of the region is flat and dry with predominantly sluggish river systems which exist as a series of pools for much of the year (Davis et al. 2010). Perennial flows occur in the wetter extreme southwest with more ephemeral conditions inland. Extensive land clearing for agriculture, combined with a poor understanding of local and regional environmental processes, has had a major impact on terrestrial and aquatic ecosystems in the southwest of Western Australia. Land clearing for annual crops and grazing has resulted in multiple disturbances to aquatic systems, including altered hydrological regimes, the loss of riparian vegetation, sedimentation, changes in thermal and light regimes, nutrient enrichment and dryland or anthropogenic salinisation (Hatton et al. 2003).

The greatest environmental change associated with agricultural activity has resulted from the replacement of deep-rooted perennial species (mainly *Eucalyptus* woodlands) with shallow-rooted annual cropping species (wheat, barley and canola). The resulting reduction in evapotranspiration altered the water balance leading to rising watertables and the mobilisation of salt once stored deep in the soil profile (Wood 1924; Mulcahy 1978; Schofield et al. 1988). As a consequence, an area of over 1 million ha, encompassing the entire wheatbelt region of south-western Australia, has been affected by rising saline watertables.

Temporary wetlands and river pools that were previously replenished by surface water runoff driven by winter rainfall are now dominated by saline groundwater inputs and permanent water regimes. Waterlogging and salinisation have resulted in the death of fringing trees, and the dominance of samphire vegetation throughout the valley floors and other low-lying parts of the landscape. Although recent drought conditions have resulted in falling watertables and a reversion to temporary regimes in some areas, elevated salinities still remain. The extent of hydrological change and anthropogenic salinisation is now so widespread as to represent a major social, ecological and economic disaster (Beresford et al. 2001). However, it must be noted that agricultural productivity and associated economic returns remain high in areas away from salt-affected valley floors.

For the rivers, streams and wetlands of the region, rising salty watertables have resulted in a transition from freshwater to saline conditions accompanied by a reduction in aquatic plant and invertebrate richness (Strehlow et al. 2005). In some areas, the occurrence of highly saline groundwater combined with the high rates of evapo-concentration associated with a Mediterranean climate (cool, wet winter and hot, dry summer), have resulted in a further transition from saline to hypersaline conditions. As a consequence, shallow lentic systems previously dominated by submerged macrophytes are now dominated by benthic microbial mats (Strehlow et al. 2005; Sim et al. 2006a, b, c). Where aquatic systems still dry on a seasonal basis, the presence of a macrophyte-dominated regime appears to follow a threshold model which is controlled by salinity alone. Macrophyte-dominated communities are seldom recorded at salinities above 45 g/L. At higher salinities, benthic microbial communities are dominant. In contrast, permanently wet systems potentially follow an alternative states model where either community could be present at relatively low salinities (Strehlow et al. 2005; Sim et al. 2006a, b, c).

Solutions to anthropogenic salinisation designed to restore agricultural productivity have included both biological and engineering approaches. These include: the planting of trees in recharge zones; the planting of salt tolerant species; the construction of shallow drains to prevent waterlogging and the use of deep drains or groundwater pumps to intercept the watertable and transport saline groundwater via surface networks further downstream. Although deep drains and groundwater pumps appear to have been successful in lowering the watertable and moving salt downstream, and require less land to be taken out of agricultural production than the replanting of perennials (Ali et al. 2004), they have also created new water quality issues. Groundwaters in the eastern wheatbelt region are often strongly acidic ($pH < 3.5$) and typically very saline (6,000–8,000 mS/m). As a consequence, deep drains in this region, which often discharge to streams or wetlands, contain high levels of iron, aluminium, cobalt, copper, zinc and lead, and during periods of low flow, exhibit extreme acidity ($pH < 3$) and salinity (10,000–20,000 mS/m) (Stewart et al. 2009).

Given the scale and severity of anthropogenic salinisation, there appears to be little prospect of restoring freshwater ecosystems in the wheatbelt. The economic returns from cropping in higher, unaffected regions of the landscape currently far outweigh the production lost in the low-lying areas affected by salinisation. As a consequence, the external economic driver, agricultural productivity, is unlikely to change. Irreversible change (from freshwater to saline or hypersaline conditions) has occurred in most of the wetlands, lakes and river pools of the salinised valley floors. This has been accompanied by a considerable loss of biodiversity. The decreases in aquatic invertebrate and plant species richness with increasing salinity have been well documented for Australian waterbodies (Hart et al. 1991; Nielsen et al. 2003; Pinder et al. 2005). However, within saline systems, stands of halotolerant submerged macrophytes (*Ruppia* spp., *Lepilaena* spp. and charophytes) will continue to support populations of halotolerant invertebrates and waterbirds, provided the thresholds for plant germination are not exceeded. Accordingly, the conservation of ecosystem processes, rather than species (Moss 2000), may be the most feasible management goal for these salt-affected systems.

Most climate change scenarios for south-western Australia suggest a drying climate. It is possible that lower annual rainfall may act to reduce the impact of current stressors. For example, recent drought in south-eastern Australia has reduced the rate of expansion of dryland salinisation because drier conditions have resulted in declining rather than rising salty water tables (Anderies et al. 2006). Climatic change may play a large part in facilitating a move from hypersaline conditions back to saline conditions. A series of dry years (during which salty watertables drop) followed by a high rainfall year means that sufficient fresh surface waters will be present to dilute many systems to below the threshold for plant germination.

Unfortunately, because salinisation in south-western Australia has occurred over very large spatial scales, and in some regions, over very long timescales (>100 years), the ecological processes that maintained fresher systems may have vanished from the landscape. The loss of these essential processes underlies irreversible change in aquatic ecosystems (Gordon et al. 2008; Fig. 6). The seedbanks that are fundamental to the development of plant-dominated, seasonally drying systems may have disappeared from landscapes now dominated by benthic microbial communities. Research is needed to determine the longevity of seedbanks and the potential for recovery if changing climatic conditions result in more frequent rainfall events and a return to fresher conditions.

The current challenges faced by both ecosystem researchers and managers are likely to increase, given that climate change and its 'top down' impacts are likely to be the dominant direct drivers of biodiversity loss and ecosystem change (Finlayson et al. 2005) in the coming years. To face these challenges for aquatic systems, we need to identify and better understand both the external drivers and internal ecosystem dynamics, and the interactions between them, at appropriate spatial and temporal scales.

Climate change—coastal salinisation in northern Australia

The vulnerability of coastal wetlands in the Alligator Rivers Region in northern Australia to climate change and sea level rise was assessed as part of a national study (Bayliss et al. 1997; Eliot et al. 1999). The coastal area comprises estuarine and freshwater habitats that are intricately interlinked. The assessment focused on the floodplain environments of the Region, but was more widely applicable to the wetland environments that occur across the northern Australian wet-dry tropics (Finlayson et al. 2009).

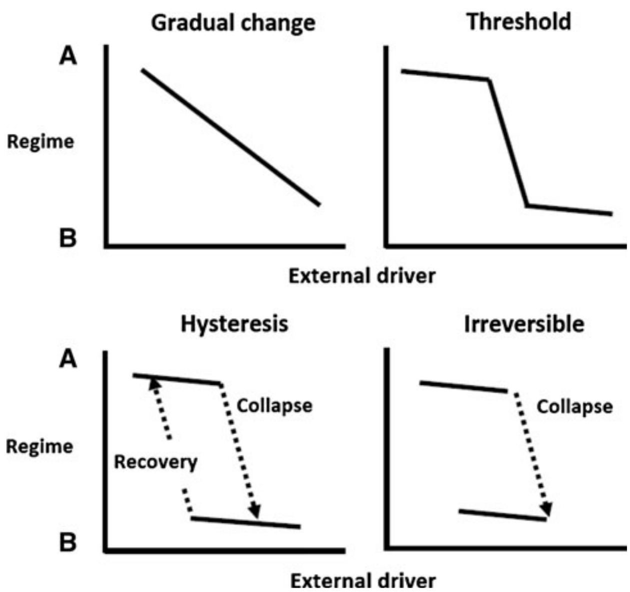

Fig. 6 Models of change between two stable ecological states from largely reversible and linear gradual change to through threshold and hysteresis to ecological collapse and irreversible change (based on Gordon et al. 2008)

The Alligator Rivers Region is isolated and compared to much of southern Australia is relatively undisturbed. It contains Kakadu National Park which has immeasurable natural and cultural value, and has attracted great interest over the past 3–4 decades. It includes vast tracts of wetland on floodplains bordering its principal rivers—the Wildman, West Alligator, South Alligator and East Alligator Rivers that drain into van Diemen Gulf. The environment of the Region is highly dynamic, physically and biologically, and is subject to extreme rates of change due to seasonal and inter-annual variation in climate, storm incidence, tidal fluctuation, and river discharge (Finlayson and Woodroffe 1996).

The coastal areas of the Region are low in elevation and susceptible to sea level rise with the floodplain wetlands generally located between 3–4 m above Australian Height Datum, which makes them only 0.2–1.2 m above mean high water level (Woodroffe et al. 1986). It was projected that a change in climate accompanied by a rise in sea level would substantively affect the physical and biological character of the wetlands on the coastal plains. It is also expected that changes to the physical and biological character would have social and economic ramifications and affect the way in which the natural resources of the Region were managed.

The floodplains that cover approximately 195,000 ha along the major rivers and creeks are underlain by riverine mud and are at elevations of less than 5 m. The floodplains contain most of the freshwater wetlands that comprise the seasonally inundated floodplains and include permanent water in lagoons and marshes. The wetting and drying of the seasonal climate have resulted in a diverse flora with characteristic wet and dry season communities that are greatly affected by the flooding regime (Finlayson and Woodroffe 1996). In the wet season, the flowering plants are diverse and profuse, while in the dry season they are sparse and less diverse. Mangroves occur close to the coast and along the tidal reaches of the major rivers and as with the freshwater vegetation they are extremely productive (Woodroffe et al. 1988; Finlayson and Woodroffe 1996). Landward of the mangroves there are broad un-vegetated saline flats fringed by chenier ridges and low levees that separate them from the freshwater wetlands. In recent times, the distribution of mangroves has been changing as a consequence of the headward expansion of tidal creeks into the freshwater wetlands (Woodroffe and Mulrennan 1993; Fig. 7).

Areas that could be affected by climatic and sea level changes were determined using a combination of physical and biological evidence. Determination of those parts of the coastal zone that could be affected was done at three scales: the biophysical region, the Alligator Rivers Region, and the floodplain of the Magela Creek, a tributary of the East Alligator River. Areas that could be affected include the full length of the shoreline of the region and the floodplains of the rivers draining into van Diemen Gulf. The Magela Creek floodplain was selected for more specific assessment based on the extensive information that had been collected for this floodplain over many years (see, for example, Finlayson et al. 1990; Finlayson and Woodroffe 1996; Wasson 1992; East 1996). The floodplain is vulnerable to saltwater intrusion in response to changes in the fluvial regime of the East Alligator River, as well as to sea level rise and shoreline retreat. Specifically, sea level rise, shoreline erosion and saltwater intrusion would change both the salt and freshwater wetlands. This would be seen in: reduction or loss of parts of the mangrove fringe along the coast line, extensive loss of *Melaleuca* (paperbark trees) along the margins of some wetlands, colonization of mangroves along creek lines as an accompaniment to salt water intrusion, and the replacement of freshwater wetlands with saline mudflats. Changes in the wetland communities and habitats will in turn result in changes in the fauna.

Oceanographic processes in van Diemen Gulf contribute to many of the changes through high rates of shoreline erosion, changing tidal regimes within the river systems, and contribution to saltwater intrusion into freshwater ecosystems. Changes resulting from these processes are seen in reduction of the fringing mangroves along the shores of the Alligator Rivers Region of the Gulf, expansion of the samphire and saltflat areas, colonization of mangroves along estuarine levee banks, and the headward

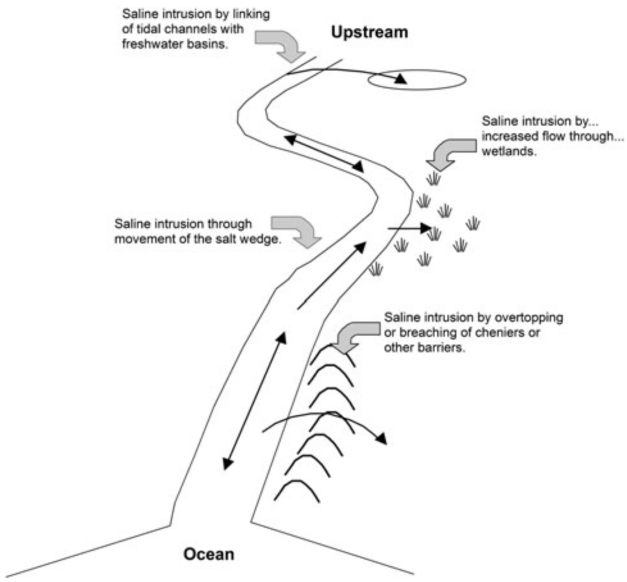

Fig. 7 Potential mechanisms for saline intrusion with distance upstream of the river mouth (adapted from Winn et al. 2006)

erosion of tidal creeks. The processes of change are interactive with those of the river systems and with human interference, particularly the introduction of feral animals and infestation of introduced plants. While the terrestrial and riverine processes of change are reasonably well researched, remarkably little is known of the hydrodynamic processes in van Diemen Gulf and their immediate impacts on the shoreline of the Alligator Rivers Region.

The floodplains in the Region are vulnerable to saltwater intrusion in response to changes in the fluvial regime of the rivers, as well as to sea level rise and shoreline retreat. There is considerable evidence of contemporary change throughout the Alligator Rivers Region and neighboring catchments that demonstrates that the coastal wetlands are undergoing very substantial alteration due to shoreline retreat, changing estuarine hydrodynamics, and saltwater intrusion (Woodroffe and Mulrennan 1993). Additionally, changes to the level, frequency, persistence and extent of wetland inundation are expected to accompany the predicted 20% increase in summer rainfall. Saltwater intrusion has been largely attributed to the impact of the feral Asian water buffalo (*Bubalus bubalis*), but more recent analysis has linked saline intrusion along the coast to the effect of drier-than average monsoonal conditions, low-frequency and low-intensity cyclonic events, and above-average ocean water levels since 1950, and particularly since the mid-1980s, associated with the loss of vegetation on the lower coastal plain (Winn et al. 2006).

Monitoring of coastal change has occurred through scientific institutions with an interest in the region and includes the headward expansion of tidal creeks and mangroves (Mitchell et al. 2007). Overall, however, governance in the Region and neighboring catchments does not seem to be geared to deal with environmental change of the type and magnitude that is currently occurring (Finlayson et al. 2009). Issues are dealt with on a sectoral basis rather than in an integrated, intergovernmental and cross-sectoral manner (Finlayson et al. 1998). Governmental structures and community based management mechanisms need to be developed to provide a consistent and appropriate response for system management, rather than addressing problems at a sectoral level.

Issues of governance within the biophysical region that includes the Alligator Rivers Region are a microcosm of conditions found elsewhere in Australia. Problems of coordination and integration are common, as are issues relating to relations between government and the wider community, particularly with regard to the development and implementation of management plans. There is a notable lack of formal mechanisms to adequately integrate the roles of the various stakeholders in environmental management. Mechanisms are required because there is a need for effective governmental relations in order that the responses to environmental change are owned and implemented by all concerned. These problems need to be systematically examined and rectified.

Discussion—policy responses

As shown by CSIRO and Australian Bureau of Meteorology (2007), only broad, imprecise projections of climate change exist. While these are on a regional scale, the regions are very large and regarded as too large in scale to provide useful guidance on the impact of climate change on wetlands. Nevertheless, for what it is worth, these projections indicate that in Australia's major watershed, the Murray-Darling Basin, conditions are likely to be slightly warmer on average by 2030, with lower and more variable rainfall. There could be implications for water resources in terms of higher evaporation rates and more variable runoff, but such predictions would need to be hedged with statements about uncertainty. Whilst there is considerable uncertainty associated with the downscaling of climate projections, the need for managing within the vagaries of a variable climate could not be greater—many of Australia's rivers and wetlands are degraded and water resources overexploited at a time when severe drought has gripped large parts of the country (Connell 2007). The changing climate, coupled with existing land and water uses, could spell a major change in the landscapes and land uses in the Basin unless clear decisions are made and options for conserving wetlands are identified and translated into on-ground outcomes (Pittock and Finlayson 2011).

In response to water allocation and drought conditions, an integrated management plan for the Murray-Darling Basin is being prepared (http://www.mdba.gov.au/basin_plan, accessed 24 January 2010). The plan will for the first time enable integrated management of the surface water and groundwater resources and restoration of the aquatic ecosystems of the Basin. In doing this, Australia is tackling a challenge that has not been achieved elsewhere—namely, to integrate water management across a large river system and restore it to a healthy state so that it can sustain its environment, enhance and maintain the services it provides, and support the communities and industries that depend on it. The plan will need to consider climate projections that suggest that this important watershed is likely to continue to be plagued by the recurrent droughts of the past. Australia is known as a land of droughts and floods with many wetlands in the Basin currently adversely affected by the drought conditions of the past decade (Baldwin and Fraser 2009). Climate change impacts will probably not change this before 2050, if then. In other words, we already have 3-year droughts that impose enormous stresses on wetlands. This is most likely to continue under climate change.

The big pressures on wetlands across Australia in recent decades have come from agriculture and from landscape changes, such as salinisation. As shown in Table 4, more than 70% of the harvested water is used for irrigation in agriculture and this use has been increasing (Beeton et al. 2006). In contrast, only 8% is used by households. An anomaly seems to be the enormous efforts expended by policy makers over the years to reduce urban consumption, while very little attention has been paid, until recently to agricultural water use. An examination of the use of water in irrigation reveals several disturbing trends. First, the amount of water used for irrigation has been increasing by about 5% per year since the mid-1980s (NLWRA 2001b). Second, this water is used in relatively unproductive uses to grow many crops that have relatively low returns (NLWRA 2001b). Indeed, Dunlop et al. (2002) showed that, over a 50-year period, a reduction of volume of water used in irrigation of 8,700 GL could be achieved by reducing the amount used on low productivity crops and pasture and through improvements in efficiency in other crops.

Table 4 Consumption of water in Australia ('000 GL) (NLWRA 2001b)

	Irrigation	Urban/industrial	Rural	Total
1983/84	10.2	3.1	1.3	14.6
1996/97	17.9	4.7	1.4	24.0

The National Water Commission (2009) reported that while there had been improvements in the use of science-based methods to determine environmental water requirements, further work is needed to integrate them into adaptive environmental management. Further, it reports that failure to use robust methods in the past has contributed to the inadequate specification of environmental objectives and flow requirements and exacerbated the debate about over-allocation and over-use across the country. The Commission was also concerned about the security of environmental water access entitlements and rules-based environmental water, particularly during drought.

This leads to a third issue, which is that water use efficiency on Australian farms is low. It has been shown over many years that efficiency depends on various factors such as the type of irrigation system and the type of agricultural system. However, Hearn et al. (1997) found efficiencies as low as 25% on many farms. Evaporation is a major problem for the largely open irrigation systems. Despite these significant efficiency problems, irrigation plays a vital role in Australian agriculture. The gross value of irrigated agriculture for 2006–2007 was $12,319 million, which was 34% of the total gross value (ABS et al. 2009). The overall picture in agriculture is of massive amounts of water being used relatively inefficiently to produce significant amounts of national production.

Another aspect of irrigated agriculture is its detrimental effects on the environment. Rising water tables resulting from irrigation have been associated with salinisation. NLWRA (2001b) reported that about 60% of river basins were found to have unacceptable levels of nutrients and turbidity. In addition, there are many studies reporting significant loss of habitat for wildlife as a result of diversion of water from the river systems (see above). It is worth examining the location of agricultural production relative to the supply of water. This reveals that the Murray-Darling Basin, which is characterized by relatively low and uncertain rainfall, is the main agricultural production region. It is not surprising that a heavy dependence on irrigation has been developing. This dependence has been a cause for concern among conservationists and ecologists who observe events like the flushing of wetlands occurring less frequently or not at all (as described above).

To this picture of agriculture in competition with the environment for the use of scarce water supplies, we must now add the recently announced policy changes relative to climate change. These take two broad forms. There is policy designed to buy back water from farms to enhance the level of environmental services, and more direct greenhouse gas reduction policy in the form of a proposed emissions trading scheme. The first step in a $3.1 billion buy back of water by the Australian Government was announced in August 2008. While there are three components mentioned, this first stage concentrates on the northern section of the Murray-Darling Basin:

1. The first comprehensive, detailed and externally reviewed audit of both public and private water storages in the Basin.
2. Initiating a new basin-wide tender in 2008–2009; and expanding the previously announced Queensland tender to include northern New South Wales and increasing funding for this program by \$50 million to \$400 million.
3. A Commonwealth-State initiative to co-fund the purchase of properties holding large water entitlements, particularly in the northern Basin.

The tender closed in December 2008, and succeeded in buying back 50 GL of entitlements. The problem is that these entitlements had less than 5 GL of water allocated to them because of the drought situation (Garrick et al. 2009). Nevertheless, farmers were willing to voluntarily sell back these water rights, and hence the policy seems like a step in the right direction, even if at the outset it seems like "paper" water.

Turning to the proposed emissions trading scheme, we find that its impacts on agriculture and thence on to wetlands are much more difficult to predict. The current plan is to exclude agriculture from the scheme. The Government of Australia envisages a cap-and-trade scheme for carbon trading. This will apply to the major greenhouse gas polluters. The major emitters are the close-to-1,000 firms which collectively account for 75% of Australia's greenhouse gas emissions. These firms will have to compete to purchase carbon permits. One permit will be required for every tonne of CO_2 equivalent emitted. Hence it will cost more to produce goods and services (e.g. electricity) that generate greenhouse gases in their processing. Even though agriculture is a major emitter (around 15–18% of total), it will be left out of the scheme, or its entry delayed. There are two important ways that agriculture could be affected. The first is that some farmers could devote part of their holdings to forestry as offsets, and sell these to emitting firms. Second, carbon-based inputs, such as fertilizer, are likely to cost more, so that at the margin there could be a substitution away from them and away from production processes that use them intensively. It is unlikely that these two changes would have much effect in a 5–6 year interim period, because forestry, for example, involves locking-up land for long periods of time, which has in the past been unattractive for most farmers. Also, there is considerable uncertainty about whether it will be necessary to buy back permits when trees are cleared.

In the longer term, when agriculture may be integrated into a cap-and-trade scheme, one would expect more dramatic changes to agriculture, and possibly to wetlands. The difficulty in any projection exercise is that there are several alternative ways of including agriculture. The two most likely are either to just charge agriculture for its emissions, that is, to require it to purchase permits to cover its emissions, or to charge it for emissions and also allow it to provide sequestrations services in its farming activities, and thereby gain revenues from offsets. In either case, there are significant administrative issues to confront related to difficulties of contracting, measurement and control.

If the scheme for agriculture was of the former type and required farms to buy permits to cover their emissions, then this would tend to penalize animal agriculture (beef, sheep, dairy, pigs) heavily. More that 50% of greenhouse gas emissions are contributed by the beef sector and about 20% by sheep farming (Keogh 2008). It is possible then to examine regional locations that concentrate on these types of agriculture and assess what the likely impacts would be following the introduction of the policy. As an example, irrigated dairy farming is a prominent activity in north-east Victoria. It may be that the tax imposed on it through the need to purchase permits under the cap-and-trade scheme will cause it to become uneconomic. This may result in improved river flows and a positive effect on wetlands, as resources are moved out of dairying.

In contrast to this, there are other regions where well-managed crop farms (in terms of agronomy) could operate in a carbon–neutral fashion. The operation of the cap-and-trade policy will encourage the shift of resources towards these farms, which will essentially avoid the tax because they won't need a carbon permit, and this could result in some negative effects for wetlands, including salinity.

One proviso to this appraisal of the impacts of the policy on agriculture is that the Australian Government is envisaging some free carbon permits for emission-intensive industries. So some of these effects may be less pronounced depending on how generous the government is with free permits. For political reasons it could be quite generous. Also, the rationale that the government has used for the allocation of free permits in other sectors of the economy is that most free permits would be offered to firms that are carbon intensive and produce tradable products. The beef and sheep sectors are the areas of agriculture that fit most easily into this category.

If the inclusion of agriculture in the emission trading scheme follows that of the alternative policy, in which sequestration receives offset credits, but emissions are still charged, then some dilution of the above pattern of impacts would result. Sequestration revenues would result from minimum and no-till cropping, and some pasture systems that maintain continuous ground cover. Hence, inclusion of agriculture in this manner would give financial benefits (perhaps small) to cropping systems, and costs to animal systems, but a lower level than under the first alternative because of the benefits received from pasture offsets.

It is also worth noting that some second-round environmental effects could result. Higher soil organic carbon levels that result from sequestration, tend to improve moisture and nutrient holding capacities. This could result in lower nutrient levels in surface and groundwater. On the other hand, where minimum and no-till systems are introduced, there is also likely to be increased use of herbicide. This could result in lower quality water exiting the farm system.

The above discussion envisages the policy impacts on wetlands occurring indirectly through policy effects on agriculture. In both the water buy back arrangements and the emissions trading scheme, the general effects through this indirect route would be expected to be positive in terms of additional water for wetlands. Another issue to consider briefly is the direct relationship between the carbon emissions scheme and wetlands. Wetland restoration may sequester carbon dioxide, but at the same time result in increased methane emissions. More research is needed on quantifying the time path of these effects and for dispelling some of the misconceptions about the role of all wetlands in storing or releasing carbon gases.

References

ABS, ABARE, BRS (2009) Socio-economic context for the Murray-Darling Basin—descriptive report. MDBA publication no. 34/09. Murray-Darling Basin Authority, Canberra

Ali R, Hatton T, George R, Byrne J, Hodgson G (2004) Evaluation of the impacts of deep open drains on groundwater levels in the wheatbelt of Western Australia. Aust J Agric Res 55:1159–1171

Anderies JM, Ryan P, Walker BH (2006) Loss of resilience, crisis and institutional change: lessons from an intensive agricultural system in southeastern Australia. Ecosystem 9:865–878

Arthington AH, Pusey BJ (2003) Flow restoration and protection in Australian rivers. River Res App 19:377–395

AWRC (Australian Water Resources Council) (1975) Review of Australia's water resources. Australian Government Publishing Service, Canberra

Baldwin DS, Fraser M (2009) Rehabilitation options for inland waterways impacted by sulfidic sediments—a synthesis. J Environ Manage 91:311–319

Bartolo R, Bayliss P, van Dam R (2008) Ecological risk assessment for Australia's northern tropical rivers. Subproject 2 of Australia's Tropical Rivers—an integrated data assessment and analysis (DET18). Environmental Research Institute of the Supervising Scientist, National Centre for Tropical Wetland Research, Darwin

Bayliss BL, Brennan KG, Eliot I, Finlayson CM, Hall RN, House T, Pidgeon RWJ, Walden D, Waterman P (1997) Vulnerability assessment of predicted climate change and sea level rise in the Alligator RiversRegion, Northern Territory, Australia. Supervising Scientist Report 123. Supervising Scientist Division, Environment Australia, Canberra

Beresford Q, Bekle H, Phillips H, Mulcock J (2001) The salinity crisis. University of Western Australia Press, Crawley

Beeton RJS, Buckley KI, Jones GJ, Morgan D, Reichelt, RE, Trewin (2006) Australia State of the Environment 2006. Department of the Environment and Heritage, Canberra

Boulton A, Lloyd LN (1991) Aquatic macroinvertebrate assemblages in floodplain habitats of the lower River Murray. Reg Riv: Res Manage 6:183–201

Bowler JM (1986) Spatial variability and hydrologic evolution of Australian lake basins: analogue for Pleistocene hydrologic change and evaporite formation. Palaeogeogr Palaeoclimatol Palaeoecol 54:21–41

Bren LJ (1992) Tree invasion of an intermittent wetland in relation to changes in the flooding frequency of the River Murray, Australia. Aust J Ecol 17:395–408

Bunn SE, Boon P, Brock MA, Schofield NJ (eds) (1997) National wetlands R&D program: scoping review. Land and Water R&D Corporation, Canberra. Occasional Paper 01/1997

Cai WJ, Jones DA, Harle K, Cowan TD, Power SB, Smith IN, Arblaster JM, Abbs DJ (2007) Past climate change. Climate change in Australia. CSIRO Marine and Atmospheric Research, Aspendale

Chivas AR, De Deckker P, Shelley JMG (1986) Magnesium and strontium in non-marine ostracod shells as indicators of palaeosalinity and palaeotemperature. Hydrobiologia 143:135–142

Commonwealth of Australia (2002) Australian Catchment, River and Estuary Assessment 2002. National Land and Water Resources Audit, Canberra

Connell D (2007) Water politics in the Murray-Darling Basin. The Federation Press, Leichardt

Conrick D, Edgar B, Innes A (2007) Development of national indicators for wetland ecosystem extent, distribution and condition. Final Report. National Land and Water Resources Audit, Canberra

CSIRO and Australian Bureau of Meteorology (2007) Climate change in Australia: technical report 2007. CSIRO, Canberra

CSIRO (2008) Water availability in the Murray-Darling Basin. A report from CSIRO to the Australian Government, CSIRO

Davis J, Lake P, Thompson R (2010) Freshwater biodiversity and climate change. In: Jubb I, Hopler P, Cai W (eds) Greenhouse 09: living with climate change. CSIRO Publishing, Melbourne, pp 73–83

De Deckker P (1986) What happened to the Australian aquatic biota 18,000 years ago? In: De Deckker P, Williams WD (eds) Limnology in Australia. Dr. W. Junk, Dordrecht, pp 487–496

De Groot R, Finlayson CM, Verschuuren B, Ypma O, Zylstra M (2008) Integrated assessment of wetland services and values as a tool to analyze policy trade-offs and management options: a case study in the Daly and Mary River catchments, northern Australia. Supervising Scientist Report 198. Supervising Scientist, Darwin

DEWHA (Department of the Environment, Water, Heritage and the Arts) (2009) National guidelines for notifying change in ecological character of Australian Ramsar sites (Article 3.2). Module 3 of the National Guidelines for Ramsar Wetlands—implementing the Ramsar Convention in Australia. Australian Government Department of the Environment, Water, Heritage and the Arts, Canberra

Dunlop M, Turner G, Foran B, Poldy F (2002) Decision points for land and water futures. Resource Futures Program Working Document 2002/08. CSIRO Sustainable Ecosystems, Canberra

East TJ (1996) Landform evolution. In: Finlayson CM, von Oertzen I (eds) Landscape and vegetation ecology of the Kakadu Region, Northern Australia. Geobotany 23. Kluwer Academic Publishers, Dordrecht, pp 37–56

Eliot I, Waterman P, Finlayson CM (1999) Monitoring and assessment of coastal change in Australia's wet-dry tropics. Wetlands Ecol Manage 7:63–81

Environmental Protection Agency (2005) Wetland mapping and classification methodology—overall framework—a method to provide baseline mapping and classification for wetlands in Queensland, version 1.2. Queensland Government, Brisbane

Finlayson CM, Rea N (1999) Reasons for the loss and degradation of Australian wetlands. Wetl Ecol Manage 7:1–11

Finlayson CM, von Oertzen IAML (1993) Wetlands of Australia: Northern (Tropical) Australia. In: Whigham DJ, Dykyova H, Heijny S (eds) Wetlands of the World I: inventory, ecology and management. Kluwer Academic Publishers, Dordrecht, pp 195–243

Finlayson CM, Woodroffe CD (1996) Wetland vegetation. In: Finlayson CM and von Oertzen I (eds) Landscape and vegetation ecology of the Kakadu Region, Northern Australia. Geobotany 23, Kluwer Academic Publishers, Dordrecht, pp 81–112

Finlayson CM, Bailey BJ, Cowie ID (1990) Characteristics of a seasonally flooded freshwater system in monsoonal Australia. In: Whigham DF, Goode RE, Kvet J (eds) Wetland ecology and management—case studies. Kluwer Academic Publishers, Dordrecht, pp 141–162

Finlayson CM, Hall RN, Bayliss BL (1997) Regional review of wetland management issues: wet-dry tropics of northern Australia. LWRRDC Occasional Paper 03/97, Canberra

Finlayson CM, Thurtell L, Storrs MJ, Applegate R, Barrow P, Wellings P (1998) Local communities and wetland management in the Australian wet-dry tropics. In: Williams WD (ed) Wetlands in a dry land: understanding for management. Environment Australia, Biodiversity Group, Canberra, pp 299–311

Finlayson CM, D'Cruz R, Davidson NC (coordinating lead authors) (2005) Ecosystems and human wellbeing: wetlands and water. World Resources Institute, Washington, DC

Finlayson CM, Gitay H, Bellio MG, van Dam RA, Taylor I (2006) Climate variability and change and other pressures on wetlands and waterbirds—Impacts and Adaptation. In: Boere G, Gailbraith C, Stroud D (eds) Water birds around the World. Scottish Natural Heritage, Edinburgh, pp 88–89

Finlayson CM, Eliot I, Eliot M (2009) A strategic framework for monitoring coastal change in Australia's wet-dry tropics-concepts and progress. Aust Geog 47:109–123

Fitzpatrick R, Marvanek S, Shand P, Merry R, Thomas M (2008) Acid sulfate soil maps of the River Murray below Blanchetown (Lock 1) and Lakes Alexandrina and Albert when water levels were at pre-drought and current drought conditions. CSIRO, Adelaide

Fitzsimmons KE, Gell PA, Bickford S, Barrows TT, Mooney SP, Denham TP, OZPACS (contributers) (2008) The OZPACS database: a resource for understanding recent impacts on Australian ecosystems. Quaternary Aust 24: 2–6

Fluin J, Gell P, Haynes D, Tibby J (2007) Paleolimnological evidence for the independent evolution of neighbouring terminal lakes, the Murray-Darling Basin, Australia. Hydrobiologia 591:117–134

Gale SJ, Haworth RJ (2005) Catchment-wide soil loss from pre-agricultural times to the present: transport-and supply-limitation of erosion. Geomorphology 68:314–333

Garrick D, Siebentritt MA, Aylward B, Bauer CJ, Purkey A (2009) Water markets and freshwater ecosystem services: policy reform and implementation in the Columbia and Murray-Darling Basins. Ecol Econ 69:366–379

Gehrke PC, Harris JH (2001) Regional-scale effects of flow regulation on lowland riverine fish communities in New South Wales, Australia. Reg Riv: Res Manage 17:369–391

Gehrke PC, Brown P, Schiller CB, Moffatt DB, Bruce AM (1995) River regulation and fish communities in the Murray-Darling river system, Australia. Reg Riv: Res Manage 11:363–375

Gell PA (1998) Quantitative reconstructions of the Holocene palaeosalinity of paired crater lakes based on a diatom transfer function. Palaeoclim-Data Model 4:1–14

Gell P, Little F (2006) Long term water quality changes in Murrumbidgee floodplain wetlands revealed by fossil diatom assemblages. In: Taylor IR, Murray PA, Taylor SG (eds) Wetlands of the Murrumbidgee River catchment: practical management in an altered environment. Fivebough & Tuckerbil Wetlands Trust, Leeton, pp 43–65

Gell P, Barker P, De Deckker P, Last W, Jelicic L (1994) The Holocene history of West Basin Lake, Victoria, Australia; chemical changes based on fossil biota and sediment mineralogy. J Paleolimn 12:235–258

Gell P, Bulpin S, Wallbrink P, Bickford S, Hancock G (2005a) Tareena Billabong—A palaeolimnological history of an ever-changing wetland, Chowilla Floodplain, lower Murray-Darling Basin. Mar Freshw Res 56:441–456

Gell P, Tibby J, Fluin J, Leahy P, Reid M, Adamson K, Bulpin S, MacGregor A, Wallbrink P, Hancock G, Walsh B (2005b) Accessing limnological change and variability using fossil diatom assemblages, south-east Australia. Riv Res Appl 21:257–269

Gell P, Fluin J, Tibby J, Haynes D, Khanum S, Walsh B, Hancock G, Harrison J, Zawecki A, Little F (2006) Changing fluxes of sediments and salts as recorded in lower River Murray wetlands, Australia. In: Rowan J, Duck R, Werrity A (eds) Proceedings of the IAHS conference, International Association of Hydrological Sciences, Dundee, UK, July 2006, 306: 416–424

Gell P, Baldwin D, Little F, Tibby HancockG (2007a) The impact of regulation and salinisation on floodplain lakes: the lower River Murray, Australia. Hydrobiologia 591:135–146

Gell P, Jones R, MacGregor A (2007b) The sensitivity of wetlands and water resources to climate and catchment change, south-eastern Australia. PAGES News 15:13–15

Gell P, Fluin J, Tibby J, Hancock G, Harrison J, Zawadzki A, Khanum S, Little F, Walsh B (2009) Anthropogenic acceleration of sediment accretion in lowland floodplain wetlands, Murray-Darling Basin, Australia. Geomorphology 108:122–126

Gillanders BM, Kingsford MJ (2002) Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. Oceanogr Mar Biol: Ann Rev 40:233–309

Giorgi F (2006) Climate change hotspots. Geophysic Res Lett 33:L08707. doi:10.1029/2006GL025734

Gitay H, Brown S, Easterling W, Jallow B et al. (2001) Ecosystems and their goods and services. In: Climate change 2001. Working Group II of the intergovernmental panel on climate change: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge, UK, pp 236–342

Gordon LJ, Peterson GD, Bennett EM (2008) Agricultural modifications of hydrological flows create ecological surprises. Trends in Ecol Evol 23:211–219

Goss KF (2003) Environmental flows, river salinity and biodiversity conservation: managing trade-offs in the Murray-Darling basin. Aust J Bot 51:619–625

Hart BT, Bailey P, Edwards R, Hortle K, James K, McMahon A, Meredith C, Swadling K (1991) A review of the salt sensitivity of the Australian freshwater biota. Hydrobiology 210:1103–1117

Hatton TJ, Ruprecht J, George RJ (2003) Preclearing hydrology of the Western Australia wheatbelt: target for the future? Plant Soil 257:341–356

Hearn AB, Cameron J, Jackson B (1997) Water use efficiency: if you don't measure it, you can't manage it! Aust. Cot Grower 18:88–94

Hennessy KJ, Fitzharris B, Bates BC, Harvey N, Howden SM, Hughes L, Salinger J, Warrick R (2007) Australia and New Zealand. Chapter 11: IPCC, 2007: climate change 2007: impacts,

adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, Van den Linden PJ, Hanson CE (eds) Cambridge University Press. Cambridge, UK, pp 507–540
Jacobs SWL, Brock M (1993) Wetlands of Australia: Southern (temperate) Australia. In: Whigham DJ, Dykyova H, Heijny S (eds) Wetlands of the World I: inventory, ecology and management. Kluwer Academic Publishers, Dordrecht, pp 244–304
Jolly ID, Walker GR, Thorburn PJ (1993) Salt accumulation in semi-arid floodplain soils with implications for forest health. J Hydr 150:589–614
Jones RN, Durack PJ (2005) Estimating the impacts of climate change on Victoria's runoff using a hydrological sensitivity model. CSIRO Atmospheric Research, Aspendale
Jones RN, Bowler JM, McMahon TA (1993) Modelling water budgets of closed lakes, western Victoria. Quatern Aust 11:50–60
Jones RN, McMahon TA, Bowler JM (2001) Modelling historical lake levels and recent climate change at three closed lakes, Western Victoria, Australia (c.1840–1990). J Hydrol 246:159–180
Jones RN, Whetton PH, Walsh KJE, Page CM (2002) Future impacts of climate variability, climate change and land use change on water resources in the Murray Darling Basin: overview and draft program of research. Murray Darling Basin Commission, Canberra
Keogh M (2008) Knowledge gaps and opportunities for research to inform and position Australian primary industries to respond to a future national greenhouse emissions trading scheme. Australian Farm Institute/Land and Water Australia, Canberra
Kingsford RT (2000a) Review: ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. Aust Ecol 25:109–127
Kingsford RT (2000b) Protecting or pumping rivers in arid regions of the world? Hydrobiologia 427:1–11
Kingsford RT (ed.) (2006) Ecology of desert rivers. Cambridge University Press, Cambridge
Kingsford RT, Johnson W (1998) Impact of water diversions on colonially nesting waterbirds in the Macquarie Marshes in arid Australia. Colon Waterbird 21:159–170
Kingsford RT, Thomas RF (1995) The Macquarie Marshes and its waterbirds in arid Australia: a 50-year history of decline. Env Manag 19:867–878
Kingsford RT, Thomas RF (2004) Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia. Env Manage 34:383–396
Kingsford RT, Brandis K, Thomas RF, Crighton P, Knowles E, Gale E (2004a) Classifying landform at broad spatial scales: the distribution and conservation of wetlands in New South Wales, Australia. Mar Freshw Res 55:1–15
Kingsford RT, Jenkins KM, Porter JL (2004b) Imposed hydrological stability on lakes in arid Australia and effects on waterbirds. Ecol 85:2478–2492
Kingsford RT, Lemly AD, Thompson JR (2006) Impacts of dams, river management and diversions on desert rivers. In: Kingsford RT (ed) Ecology of Desert Rivers. Cambridge University Press, Cambridge, pp 203–247
Kingsford RT, Halse SA, Porter JL (2008) Aerial surveys of waterbirds—assessing wetland condition—final report to the National Land & Water Resources Audit. University of New South Wales, Sydney
Kingsford RT, Fairweather PG, Geddes MC, Lester RE, Sammut J, Walker KF (2009) Engineering a crisis in a Ramsar wetland: the Coorong, Lower Lakes and Murray Mouth, Australia. Australian Wetlands and Rivers Centre, University of NSW, Sydney
Koehn JD (2004) Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways. Freshw Biol 49:882–894
Lada H, Thomson JR, Mac Nally R, Horrocks G, Taylor AC (2007) Evaluating simultaneous impacts of three anthropogenic effects on a floodplain-dwelling marsupial Antechinus flavipes. Biol Conserv 134:527–536
Lada H, Thomson JR, MacNally R, Taylor AC (2008) Impacts of massive landscape change on a carnivorous marsupial in south-eastern Australia: inferences from landscape genetics analysis. J Appl Ecol 45:732–1741
Lake PS (2008) Drought, the "creeping disaster". Effects on aquatic Ecosystems. Land & Water Australia, Canberra
Leslie D (2001) Effect of river management on colonially-nesting waterbirds in the Barmah–Millewa Forest, South-Eastern Australia. Reg Riv: Res Manage 17:21–36
Lowry J, Finlayson CM (2004) A review of spatial datasets for wetland inventory in northern Australia. Supervising Scientist Report 178, Darwin
Lukacs GP, Finlayson CM (2010) An evaluation of ecological information on Australia's northern tropical rivers and wetlands. Wetl Ecol Manage 18:597–625
MacGregor AJ, Gell PA, Wallbrink PJ, Hancock G (2005) Natural and post-disturbance variability in water quality of the lower Snowy River floodplain, Eastern Victoria, Australia. River Res App 21:201–213
Magee JW, Bowler JM, Miller GH, Williams DLG (1995) Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. Palaeogeog Palaeoclimat Palaeoecol 113:3–42
Maheshwari BL, Walker KF, McMahon TA (1995) Effect of regulation on the flow regime of the River Murray, Australia. Reg Riv Res 10:15–38
MDBMC (1994) The algal management strategy for the Murray-Darling Basin: a component of the natural resources management strategy. Murray-Darling Basin Ministerial Council, Canberra
McComb AJ, Lake PS (eds) (1988) The conservation of Australian wetlands. Surrey Beatty & Sons, Sydney
MDBC (2003) Preliminary investigations into observed River Red Gum decline along the River Murray below Euston. Technical Report 03/03, Murray-Darling Basin Commission, Canberra
Mitchell AL, Lucas RM, Donnelly BE, Pfitzner K, Milne AK, Finlayson CM (2007) A new map of mangroves for Kakadu National Park, Northern Australia, based on stereo aerial photography. Aquat Conserv: Mar Freshw Ecosys 17:446–467
Moss B (2000) Biodiversity in fresh waters—an issue of species preservation or system functioning ? Environ Conserv 27:1–4
Mulcahy MJ (1978) Salinisation in the south-west of Western Australia. Search 9:269–272
National Water Commission (2009) Australian water markets report 2007–2008. National Water Commission, Canberra
Nebel S, Porter JL, Kingsford RT (2007) Long-term trends of shorebird populations in eastern Australia and impacts of freshwater extraction. Biol Conserv 141:971–980
Nielsen D, Brock MA (2009) Modified water regime and salinity as a consequence of climate change: prospects for wetlands of Southern Australia. Clim Change 95:523–533
Nielsen DL, Brock MA, Rees GN, Baldwin DS (2003) Effects of increasing salinity on freshwater ecosystems in Australia. Aust J Botany 51:655–665
NLWRA (National Land & Water Resources Audit) (2001b) Australian water resources assessment 2000. Surface water and ground water—availability and quality. National Land and Water Resources Audit, Canberra
Ogden RW (2000) Modern and historical variation in aquatic macrophyte cover of billabongs associated with catchment development. Reg Riv: Res Manage 16:487–512
Olley J, Wallbrink P (2004) Recent trends in turbidity and suspended sediment loads in the Murrumbidgee River, NSW, Australia. Inter Assoc Hydrol Sci Public No. 288:125–129

Palutikof JP (2010) The view from the front line: adapting Australia to climate change. Global Environ Change 20:218–219

Phillips W, Muller K (2006) Ecological character of the Coorong, Lakes Alexandrina and Albert Wetland of International Importance. Department for Environment and Heritage, Adelaide

Pinder AM, Halse SA, McRae JM, Shiel RJ (2005) Occurrence of aquatic invertebrates of the wheatbelt region of Western Australia in relation to salinity. Hydrobiologia 543:1–24

Pittock J, Finlayson CM (2011) Australia's Murray-Darling Basin: freshwater ecosystem conservation options in an era of climate change. Mar Freshw Res 62:232–243

Pittock AB, Nix HA (1986) The effect of changing climate on Australian biomass production: a preliminary study. Clim Change 6:243–255

Pittock B, Wratt D, Basher R, Bates B, Finlayson M, Gitay H, Woodward A (2001) Australia and New Zealand. In: Climate change 2001. Working Group II of the intergovernmental panel on climate change: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge, UK

Pittock J, Finlayson CM, Gardner A, McKay C (2010) Changing character: the Ramsar Convention on Wetlands and climate change in the Murray-Darling Basin, Australia. Environ Plan Law J 27:401–425

Poff NL, Brinson M, Day J (2002) Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States. Pew Center on Global Climate Change, Arlington

RA NLW (2001) Nutrient loads to Australian rivers and estuaries. Australian Agriculture Assessment Volume 1. National Land and Water Resources Audit, Canberra, pp 191–217

Reid MA, Sayer CD, Kershaw AP, Heijnis H (2007) Palaeolimnological evidence for submerged plant loss in a floodplain lake associated with accelerated catchment erosion (Murray River, Australia). J Paleolimnol 38:191–208

Roy PS (1984) New South Wales estuaries: their origin and evolution. In: Thom BG (ed) Coastal geomorphology in Australia. Academic press, Sydney, pp 99–121

Schofield NJ, Ruprecht JK, Loh IC (1988) The impact of agricultural development on the salinity of surface water resources of southwest Western Australia. Report WS27. Water Authority of Western Australia, Perth

Schumm SA (1968) River adjustment to altered hydrologic regimen—Murrumbidgee River and palaeochannels, Australia. US Geological Survey Professional Paper 598

Sim L, Chambers J, Davis J (2006a) Ecological regime shifts in salinised wetland systems. I. Salinity thresholds for the loss of submerged macrophytes. Hydrobiologia 573:89–107

Sim L, Davis J, Chambers J (2006b) Ecological regime shifts in salinised wetland systems. II. Factors affecting the dominance of benthic microbial communities. Hydrobiologia 573:109–131

Sim L, Davis J, Chambers J, Strehlow K (2006c) What evidence exists for alternative ecological regimes in salinising wetlands? Freshw Biol 51:1229–1248

Spiers AG, Finlayson CM (1999) An assessment of the extent of wetland inventory data held in Australia. In: Finlayson CM, Spiers AG (eds) Techniques for enhanced wetland inventory, assessment and monitoring. Supervising Scientist Report 147. Supervising Scientist Group, Canberra, pp 1–43

Steinfeld C, Kingsford RT (2008) Floodplain development and vegetation health on the Macquarie River floodplain of the Murray-Darling Basin. University of New South Wales, Sydney

Stewart B, Strehlow K, Davis J (2009) Impacts of deep drains on water quality and biodiversity receiving waterways in the Wheatbelt of Western Australia. Hydrobiologia 619:103–118

Strehlow K, Davis J, Sim L, Chambers J, Halse S et al (2005) Temporal changes between ecological regimes in a range of primary and secondary salinised wetlands. Hydrobiologia 552:17–31

Thoms MC, Sheldon F (2000) Water resource development and hydrological change in a large dryland river: the Barwon-Darling River, Australia. J Hydrol 228:10–21

Thoms MC, Beyer PH, Rogers KH (2006) Variability, complexity and diversity—the geomorphology of river ecosystems in dryland regions. In: Kingsford RT (ed) Ecology of desert rivers. Cambridge University Press, Cambridge, pp 47–75

Torgersen T, De Deckker P, Chivas AR, Bowler JM (1986) Salt lakes: a discussion of processes influencing palaeoenvironmental interpretation and recommendations for future study. Palaeogeog Palaeoclimatol Palaeoecol 54:7–19

Vivès B, Jones R (2005) Detection of abrupt changes in Australian decadal rainfall variability (1890–1989). CSIRO Atmospheric Research Technical Paper No. 73, Canberra

Wasson RJ (ed) (1992) Modern sedimentation and late quaternary evolution of the Magela Creek Plain. Research Report 6. Supervising Scientist for the Alligator Rivers Region. Australian Government Publishing Service, Canberra

White SD, Ganf GG, Oliver R (2008) Water allocation to River Murray wetlands: a basin-wide modeling approach. Land & Water Australia, Canberra

Williams M, Prescott JR, Chappell J, Adamson D, Cock B, Walker K, Gell P (2001) The enigma of a late Pleistocene wetland in the Flinders Ranges, South Australia. Quatern Inter 83–85:129–144

Winn KO, Saynor MJ, Eliot MJ, Eliot IG (2006) Saltwater intrusion and morphological change at the mouth of the East Alligator River, Northern Territory. J Coastal Res 22:137–149

Wong P (2008) Minister for Climate Change and Water. Speech to the 4th Annual Australian Water Summit. Sydney Convention and Exhibition Centre. 29–30 April 2008. Water for the future (http://www.environment.gov.au/minister/wong/2008/pubs/sp20080429.pdf, accessed 23/10/09)

Wood WE (1924) Increase of salt in soils and streams following the destruction of native vegetation. J Roy Soc West Aust 10:35–47

Woodroffe CD, Mulrennan ME (1993) Geomorphology of the lower Mary River Plains Northern Territory. Australian National University North Australia Research Unit and Conservation Commission of the Northern Territory, Darwin

Woodroffe CD, Chappell JMA, Thom BG, Wallensky E (1986) Geomorphological dynamics and evolution of the South Alligator tidal river and plains. Mangrove Monograph No 3. Australian National University, North Australian Research Unit, Darwin

Woodroffe CD, Chappell J, Thom BG (1988) Shell middens in the context of estuarine development, South Alligator River, Northern Territory. Archaeol Anthropol Oceania 23:95–103