

Engineering a Crisis in a Ramsar Wetland:

the Coorong, Lower Lakes and Murray Mouth, Australia



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Executive Summary

The Coorong, Lower Lakes and Murray Mouth (CLLMM) in South Australia, at the end of the Murray-Darling river system, were declared a Ramsar *Wetland of International Importance* in 1985. Historically, the wetland has relied on inflows from the River Murray. These began to decline after irrigated agriculture was established along the river in the late 19th Century, and seawater incursions to the CLLMM increased until construction of tidal barrages near the mouth was completed in 1939-40. Flows continued to decline with the building of dams upstream and increased diversions throughout the Murray-Darling Basin. Despite the imposition of a ‘cap’ on diversions in 1995, flows were further reduced by a decade-long drought. At least another decade of average or greater rainfall is now needed to restore the Basin’s reservoirs to full capacity. At the Murray Mouth, long-term median annual flows declined by 71%, with a 89-96% reduction in the driest 20% of years. Water levels in Lake Alexandrina and Lake Albert have fallen below sea level and the salinity of the Coorong has increased while the Murray Mouth requires continual dredging. Building weirs and other regulatory structures, pumping water to flood the exposed areas and limestoning, mulching and planting are addressing a threat from newly-exposed Acid Sulfate Soils (ASS) around the lake margins. There is a plan to pump hypersaline water from the Coorong to the ocean, to offset increasing hypersalinity in the South Lagoon caused by a lack of freshwater inflows. A last-resort option is to abandon the wetland as a freshwater environment and open the barrages to allow seawater into the lakes. Projected rises in sea level, associated with global warming, suggest that the sea could invade the region in 25-50 years; if this is correct then, there are limited prospects for long-term management of the Lakes as a freshwater system. The ecological character of the CLLMM is changing rapidly. For example, bird numbers have declined sharply, species of freshwater fish are threatened and diadromous species are denied passage between the river and ocean. Calcareous masses formed by the tubeworm *Ficopotamus enigmaticus*, an invasive brackish-water polychaete, have proliferated in Lake Alexandrina and killed many freshwater turtles. There are socioeconomic impacts on regional agriculture, boating, fishing and tourism. Governments are planning to spend up to \$2 billion on engineering interventions, planting, other mitigation programs, community initiatives and securing water for Adelaide, as well as schemes to recover water for the environment, but progress is slow. The short-term future of the CLLMM is in the hands of the South Australian Government, and its long-term future will depend on how

much water state and Commonwealth governments can recover for the environment *via* a Basin Plan developed by the Murray-Darling Basin Authority (MDBA) in compliance with the federal *Water Act 2007*. A target of an annual median flow of 3,800 GL at the barrages represents a flow that would restore low flows (below the median) when the system is most vulnerable to about one third of natural volume, considerably below historical levels, but probably allowing establishment of an estuarine-freshwater ecosystem in the Lower Lakes. This would represent an increase of about 700 GL (6%) in median annual flows at the barrages to be managed through flow rules. The unsustainable state of the CLLMM fails to meet a key objective of the National Water Initiative, signed by most governments in 2004 to return overallocated systems to environmentally-sustainable levels of extraction. We endorse some government initiatives, but have reservations about the long-term consequences of engineering works and contend that fragmentation of the regional environment to expedite management is not consistent with ecological science or wise natural resource management in the long term. We also acknowledge that the quantities of water required to secure the CLLMM are considerable, particularly given the competing demands from human consumers and other parts of the environment. There is a perception that there is insufficient water in the system and that the CLLMM will be deprived of flows as global climate change progresses and eventually be inundated by rising sea levels. These risks exist but with careful management of water resources and a level of sophistication not yet approached in the management history of the Murray-Darling Basin, the CLLMM can be saved, albeit an immense challenge for communities, their governments and agencies.

Recommendations

1. As part of the *Basin Plan*, the Murray-Darling Basin Authority (MDBA) should establish as a target, a median annual flow at the barrages of at least 3,800 GL. Such a flow would restore low flows (below the median) when the system is most vulnerable to about one third of natural volume. This would represent an increase of about 700 GL (6%) in median annual flows at the barrages. This is considerably below historical levels, but probably is a minimum requirement for an estuarine-freshwater ecosystem in the Lower Lakes and, with management of the barrages, should restore conditions favourable for waterbird populations in the Coorong. Flow could also be managed to ensure fish passage and reinstate a range of floods.
2. In the short term, vigorous efforts are needed to recover fresh water for the Coorong Lower Lakes and Murray Mouth and riparian wetlands along the Murray below Lock 1 (Blanchetown). Claims that too little water is available demonstrate the low priority given to critical environmental needs. By implication, environmental needs on the scale of the CLLMM can be met only if there is a major flood or sustained rainfall to fill upstream reservoirs.
3. Water levels in Lake Alexandrina and Lake Albert should be restored to +0.3 (approx. sea level) to +0.8 m AHD, and allowed to vary rather than being kept stable.
4. The Australian Government could commission an independent public review of scientific knowledge of the Coorong Lower Lakes and Murray Mouth and the science that underpins present and planned interventions (e.g. weirs). This should include a critical appraisal of the threat represented by acid sulfate soils (ASS) and methods for mitigation, as a basis for immediate action and later for adaptive management processes.
5. The proposal to build a 'temporary' weir across the Murray at Pomanda Island, at the junction of the River Murray and Lake Alexandrina should be abandoned. This is planned to secure a potable water supply for Adelaide and rural towns in the event of continued drought, or highly saline water in Lake Alexandrina, but its incidental ecological effects would be overwhelmingly negative. Part of the supply will be met by the recent decision to construct a desalination plant at Port Stanvac, Adelaide. Also, an increase in flows would potentially avoid any need for a weir.
6. The proposal to open the barrages and admit seawater to the Lower Lakes also should be abandoned, as it would irrevocably change the freshwater character of the lakes. If the proposal were implemented, a weir at Pomanda Island would be inevitable.

7. Immediate steps are needed to protect environmental values in the main body of Lake Alexandrina, which is continuing to regress and become more saline. Its decline will be accelerated by weir construction and pumping.
8. Lake Albert should be restored and maintained as a freshwater environment, and one option is to dig a channel between the lake and the Coorong therefore should be abandoned.
9. There should be adaptive governance, planning and management, requiring a 'vision', objectives and targets that are achievable, measurable and open to review. This should engage all stakeholders. Development of a long-term plan has commenced, under the aegis of the South Australian Department for Environment and Heritage, with funding from the Australian Government.
10. For long-term management of the Coorong, Lower Lakes and Murray Mouth, consideration should be given to forming a joint steering committee of the South Australian Department for Environment and Heritage, the Murray-Darling Basin Authority and the federal Department of Environment, Water, Heritage and the Arts.
11. Better hydrological data are needed for the Coorong Lower Lakes and Murray Mouth. This should include modelling inflows under scenarios that include a more equitable balance than prevails between the needs of the environment and human consumers. Modelling should include options from *The Living Murray* initiative, the buy-back program, water-use efficiency measures, sustainable diversion limits and *Basin Plan* arrangements, using historical flows and climate change scenarios.
12. The Australian Government should reconsider the Ramsar listing of the Coorong Lower Lakes and Murray Mouth with a view to a more realistic basis for sustainable management, should all the values for which the wetland was nominated no longer apply.

Introduction

In 1971, Australia and other countries committed to conserve the ecological character of significant wetlands (Ramsar Convention for Wetlands of International Importance 1971). Despite this, many wetlands around the world are adversely affected by water resource development (Lemly *et al.* 2000; Kingsford *et al.* 2006), including many of the 16 Ramsar-listed sites in the Murray-Darling Basin (1,059,000 km²) (e.g. Sharley and Huggan 1996; Kingsford 2000a; Kingsford and Thomas 1995, 2004; Arthington and Pusey 2003). About 10,000 GL are diverted each year across the Murray-Darling Basin and over 1,000 GL are

lost from irrigation channel and pipe networks (CSIRO 2008b); over 95% of the diversions are for irrigation (CSIRO 2008b). Before development, about 52% of the surface water of the Basin reached the sea (~11,600 GL, Table 1) while the remaining 48% sustained wetlands and floodplains and contributed to groundwater recharge (CSIRO 2008b). Adelaide (1.1 million people) depends on River Murray water for 40-60% (~100GL y⁻¹) of its annual water; this increases to more than 90% when local rainfall is low.

The Coorong, Lower Lakes and Murray Mouth (CLLMM) is a 140,500 ha complex of shallow lakes, streams, lagoons and wetlands in South Australia, at the terminus of the Murray-Darling Basin (Fig. 1). The complex was recognised as a Ramsar site in 1985 for its physical and biological diversity and spectacular populations of migratory shorebirds (Phillips and Muller 2006). Escalating demands for water and mis-management by successive state and federal governments have depleted inflows of fresh water. As a result, there is an ecological crisis in the CLLMM, foreshadowed by closure of the Murray Mouth in 1981 and continued dredging (\$5.2 million y⁻¹) since 2002 (Plate 1). Since 2006, salinities in the North and South lagoons of the Coorong have increased and falling water levels have exposed Acid Sulfate Soils (ASS) around the margins of Lake Alexandrina, Lake Albert and tributary streams (Fig. 1). The abundances of many species, including shorebirds and other waterbirds, have declined sharply over the past two decades (e.g. Paton *et al.* 2009). In 2008, the South Australian and Australian Governments formally acknowledged that the ecological character of the CLLMM Ramsar site has changed (Article 3.2 of the Ramsar Convention).



Plate 1. Dredge maintaining the Murray Mouth (5.2 million y⁻¹) which is critical for the health of the Coorong, under low or no flow conditions (R.T. Kingsford, Nov 2007).

In this paper, we examine the origins and effects of the crisis. We outline the ecological and biophysical state of the CLLMM (see Brookes *et al.* 2009, in review), but focus primarily on a critical examination of historical, current and future management. We consider whether management responses are sufficient to maintain one of our more diverse and significant wetlands, in keeping with Australia's national and international obligations.

The Ramsar wetland

The River Murray is joined by the Darling River at Wentworth (Plate 1), New South Wales, 830 river-km from its entrance to the Southern Ocean near Goolwa, South Australia (Fig. 1). Over the long-term, the Lower Murray receives about 90% of its annual flow from the Murray and its tributaries in New South Wales and Victoria (Goss 2003; Walker 2006), and the remainder is from the Darling (Breckwoldt *et al.* 2004). The Lower Murray fills the Lower Lakes (Plate 3, Fig. 1): Lake Alexandrina (area at 0.75 m AHD 64,900 ha; volume



Plate 2. The Darling river (right hand side) joins the River Murray (larger river). Most of the flows (~90%) to the Coorong, Lower Lakes and Murray Mouth come from the River Murray (R.T. Kingsford, Nov 2007).



Plate 3. The River Murray (left hand side) entering Lake Alexandrina (R.T. Kingsford, Nov 2009).

1,610 GL; mean depth 2.8 m) and Lake Albert (1,710 ha; 270 GL; 1.7 m). Lake Alexandrina also receives small annual inflows from the Finnis River and Currency Creek (~70 GL) and smaller streams draining the Eastern Mount Lofty Ranges (CSIRO 2008a; [Fig. 1](#)). The data for tributaries are imprecise because there are losses to floodplains and wetlands downstream of the last gauges in these catchments. Flows pass through Lake Alexandrina and exit to the Southern Ocean through the Goolwa Channel and channels between low islands to the Coorong and Murray Mouth ([Plate 4](#), [Fig. 1](#)).

Prior to barrage construction, Lake Alexandrina generally was fresh water (Barnett 1993; Sim and Muller 2004; Fluin *et al.* 2007). This is shown by the fossilised remains of diatoms, including salt-sensitive species, deposited in the lake sediments over the last 7,000 years (Barnett 1993; Fluin *et al.* 2007). Sediment cores show that the estuarine environment was limited to the Goolwa Channel ([Fig. 1](#)). This area was, and is, known to aboriginal Ngarrindjeri people as ‘the meeting of the waters’. There is some evidence of minor marine incursions into the main body of Lake Alexandrina, but less than 5% of total diatom taxa come from estuarine or marine environments (Fluin *et al.* 2007). This is less frequent than indicated by modelling of marine incursions (17% of years before development: MDBC 2008). Lake Albert also was mainly fresh water (Fluin, J. pers. comm.).

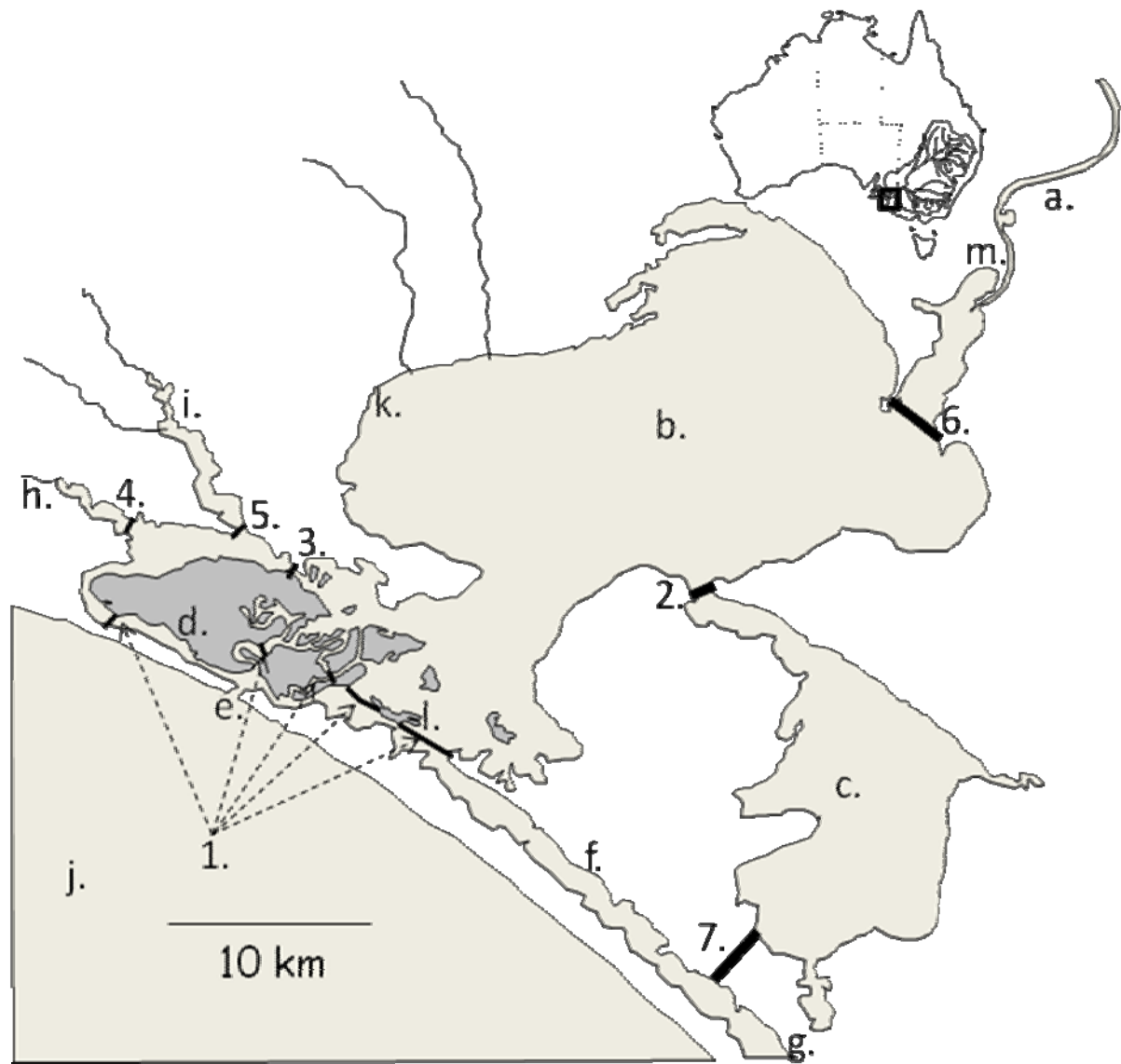


Figure 1. a. Location (rectangle) of the Coorong, Lower Lakes, Murray Mouth (CLLMM) Ramsar site on the River Murray, within the Murray-Darling Basin in south-eastern Australia. Detail of the CLLMM showing the River Murray (a), Lake Alexandrina (b), Lake Albert (c), Goolwa Channel (d), Murray Mouth (e) the North Lagoon of the Coorong (f), South Lagoon of the Coorong (g), Currency Creek (h), Finniss River (i), Encounter Bay in the Southern Ocean (j), Milang Jetty (water level data) (k), Tauwichee Barrage (salinity data) (l), and the town of Wellington (m). The engineered structures, in order of completion or planning are the (1) Barrages (completed 1939-1940), (2) the levee and regulator between Lake Alexandrina and Lake Albert (May 2009), (3) the Clayton Weir (August 2009), (4) Currency Creek Weir (September 2009) and (5) Finniss River Weir (planned), (6) Pomanda Weir (planned) and (7) the channel between Lake Albert and the North Lagoon of the Coorong (planned).



Plate 4. Aerial view of the Murray Mouth, looking north from the Coorong towards the town of Goolwa (R.T. Kingsford, Nov. 2007).

The Coorong, an inter-dune coastal lagoon, extends about 110 km south-eastward after the area around the Murray Mouth and is divided into North and South Lagoons (Fig. 1); the former is usually less saline, but salinity gradients vary with freshwater inflows (Geddes and Butler 1984; Geddes 1987, 2005; Brookes *et al.* 2009, in review). During dry periods, water levels in the Coorong are related to sea level, particularly in summer when freshwater flows over the barrages are low and the tidal prism is reduced. At this time, there is limited connectivity between the North and South Lagoons, and the salinity in the South Lagoon increases when evaporation is high, increasing salinity (Webster 2005). In winter, sea levels rise and fill the South Lagoon. Large barrage flows counteract this, by maintaining higher water levels throughout the Coorong, reducing the disconnection and lower salinities. Since 2002, some fresh water ($<10 \text{ GL y}^{-1}$) also comes to the Coorong from the Upper South East Drainage (USED) scheme *via* Salt Creek.

The CLLMM is a popular destination for tourism and recreation in South Australia, and the Coorong National Park in 2008 attracted 138,000 visitors (DEH 2009). The Gross Regional Product in 2006-2007 was about \$700M, including \$145M from primary industries (Plate 5), of which \$70M was from irrigated agriculture (DEH 2009). The fishery in the Lower Lakes

and the Coorong involves 37 fishers and produces at least \$5.5 million per annum (Plate 6, Hera-Singh 2002, EconSearch 2006). The recreational boating industry in 2003 had an estimated value of \$14.2 million, employing 140 people (Helicon 2004). Changes in the CLLMM have had major social and economic effects in the region, including reductions in dairy farms and livestock numbers (Plate 5), and downturns in wine production and the irrigation industry generally. Communities are concentrated in the towns of Goolwa, Clayton, Miland and Meningie (Plate 7). For the Ngarrindjeri, traditional inhabitants of the country, there is a deep sense of loss because the region is central to their culture (Ngarrindjeri Tendi 2006).



Plate 5. Cattle around the margins of Lake Alexandrina rely on the freshwater lake for drinking water (R.T. Kingsford, Nov. 2009).



Plate 6. Fishing is one of the important economic drivers of the Coorong, Lower Lakes and Murray Mouth region (R.T. Kingsford Nov. 2009).



Plate 7. The town of Meningie on Lake Albert is particularly affected by lowering of water levels as a result of diminishing flows in the River Murray (R.T. Kingsford, Nov. 2009).

Origins of the crisis

Water resource governance

The crisis in the CLLMM stems largely from water management upstream. Under the federal Constitution, the States have primary responsibility for water management (Connell 2007). In 1983, the Murray-Darling Basin Commission replaced the River Murray Commission and assumed responsibility for environmental management, amidst concern over salinity, eutrophication and declining river health. Under the *Murray-Darling Basin Agreement* (1985), South Australia was guaranteed an entitlement of 1850 GL y^{-1} (696 GL y^{-1} dilution flow, 1154 GL y^{-1} diversions: CSIRO 2008b), although flows to South Australia generally exceeded this entitlement. Further, the entitlement was intended and managed mainly for irrigation, with no reference to environmental flows. Environmental flow needs are concessional and given a lower priority than “critical human needs”. Even when water reached the Lower Lakes, it could be diverted for local irrigation, controlled by the barrages that allowed “surcharge” of the lakes with fresh water ($+0.85\text{m AHD}$). The 1995 “Cap” on Basin-wide diversions, administered by the Murray-Darling Basin Commission, was

designed to limit diversions to those that prevailed in 1993-1994 (MDBMC 1996: Fig. 2), but it has been only a qualified success. Queensland became a signatory in 1996 but implemented the Cap later with variable timing of plans for different catchments and so that development occurred in the interim (Kingsford 2000b). Also, diversions from floodplains were never incorporated into management of the Cap (Steinfeld and Kingsford in review).

In 2002, a scientific panel convened by the Murray-Darling Basin Commission (Jones *et al.* 2002) recommended that increased allocations were needed to offset burgeoning environmental problems in the Murray. The panel undertook a risk assessment to suggest that an additional annual flow of 1,500 GL was needed for a moderate chance of a ‘healthy’ working river. Governments agreed to allocate 500 GL to the river, mainly through infrastructure developments (i.e. increasing water efficiency). This commitment was intended for delivery by June 2009, but is yet to be realized. The water was to be deployed at six ‘icon sites’ that

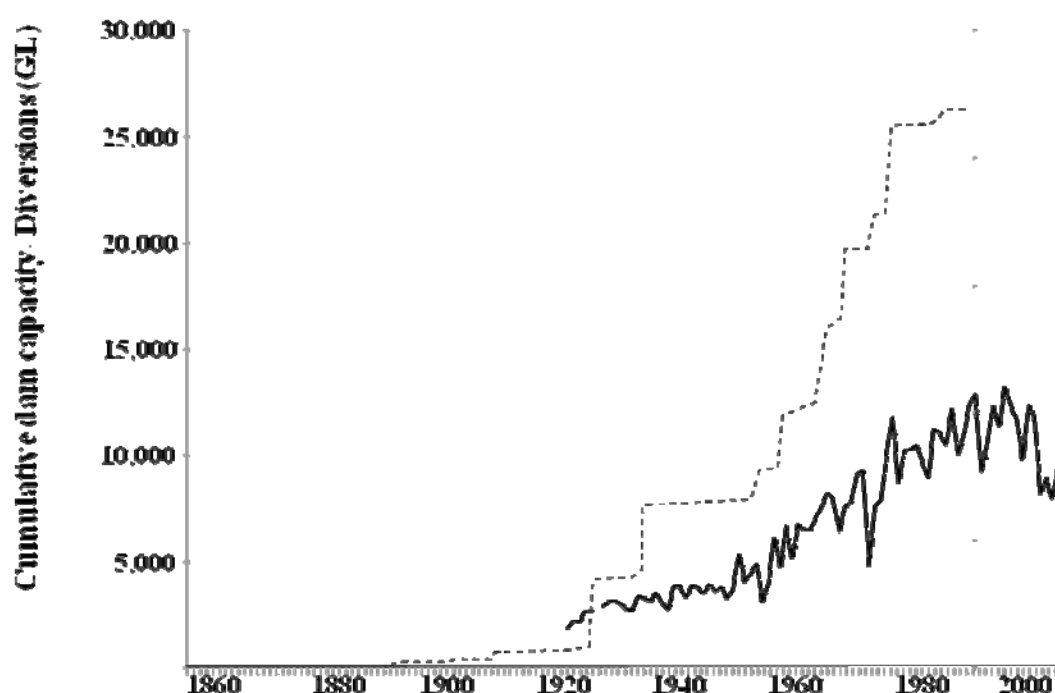


Figure 2. Cumulative capacity (solid line) for dams and reservoirs built for the storage of water, predominantly for irrigation within the Murray Darling Basin. Dashed line shows the trajectory for diversions of water from the Murray-Darling Basin, upstream of the Lower Lakes, Murray Mouth and the Coorong.

included the Murray Ramsar sites and the river channel. At the same time, water originally diverted to the Snowy-Mountains Hydroelectric Scheme was re-diverted as environmental flow to the coastal Snowy River (only 1% of natural flow levels remaining) (Erskine *et al.*

1999). Governments agreed to restore 21% of mean annual flow in the Snowy River, with an interim target of 15% by 2009, but this commitment also is still to be realised.

Drought ushered in the new millennium, and still persists (2009) with an intensity rivaling the worst historical droughts, but the effects have been deepened by the entrenched requirements of irrigation and other consumers. In 2008, the Australian Government announced a \$12.9 billion plan, *Water for the Future* (Wong 2008), to complement reforms introduced by the Council of Australian Governments (COAG) in 1994 and the *National Water Initiative* (NWI) in 2004. The *Water Act 2007* became effective in March 2008, establishing the Murray-Darling Basin Authority (MDBA) in place of the Murray-Darling Basin Commission. There was \$5.8 billion dedicated to improved water-use efficiency and \$3.1 billion to ‘buy back’ irrigation entitlements for use by the Commonwealth Environmental Water Holder in the federal Department of Environment, Water, Heritage and the Arts. Under the Act, the MDBA is responsible for monitoring water resources, reviewing state water-resource plans, engaging with the community and producing a *Basin Plan* that, by 2011, will set environmentally-sustainable limits on diversions, ensuring sufficient water for ‘critical human needs’.

Upstream water resource development

Dam construction increased rapidly after 1930, with construction of Hume Dam (1932-1936, Plate 8), and further works through the 1950s, 1960s and 1970s (Fig. 2), including establishment of irrigation settlements for returned soldiers, increased capacity at Hume Dam, the Snowy Mountains Hydroelectric Scheme and Dartmouth Dam on the Mitta Mitta River (Plate 9), above Lake Hume (Kingsford 1995, 2003; Maheshwari *et al.* 1995; Erskine *et al.* 1999, Pigram 2000). The Basin now has most dams (232) and storage capacity (29,980 GL) of the 12 major drainage divisions in Australia (Geoscience Australia 2003). Total storage capacity in the Basin exceeds annual flow by about 40% (Goss 2003), but this does not include private off-river storages (e.g. 2,435 GL in Darling River catchments: Kingsford 2004).



Plate 8. Hume Dam (3,038 GL) is the only dam on the River Murray, and one of the major regulating storages in the system (R.T. Kingsford 2009).



Plate 9. Dartmouth Dam (4,000 GL) on the Mitta Mitta River is the largest dam regulating flows in the River Murray (R.T. Kingsford, Oct. 2004).

Annual flows to the Lower Murray have declined considerably, compared to natural flows (Table 1). The estimated long-term (1895-2006) modelled median annual discharge of the Murray-Darling Basin *without* development is 10,764 GL, and 3,075 GL *with* development, indicating a 71% decrease (Table 1). The disparity between regulated and unregulated median flows increases in times of drought; in the driest 20% of years the gap is 89%, compared to 96% in the driest 5% of years (Table 1). After the turn of the millennium (2000-2008), the median annual flow at Lock 1 declined to 1,366 GL, an 88% reduction compared to modelled natural flow estimates. In 2007-2009 there was no flow over the barrages, as the Lower Lakes have remained below mean sea level. Modelling indicates that flows through the Murray Mouth have ceased (due to upstream abstraction) 40% of the time, compared to one percent of the time expected under modelled natural flow conditions (CSIRO 2008b).

Table 1. Mean, median and dry years indicated by low percentiles (80th, 90th, 95th) for annual modelled flow (GL) at the barrages in the CLLMM (Fig. 1), without development and current development conditions, 1895-2006 and ratios between these scenarios. Data from Murray-Darling Basin Sustainable Yields Project, courtesy CSIRO 2008.

Variable	Mean	Median (50 th percentile)	80 th percentile	90 th percentile	95 th percentile
Without development	11,597	10,764	6,566	5,179	3,259
Current	4,734	3,075	690	358	138
Current/Without development	41%	29%	11%	7%	4%

Implications for the Ramsar wetland

With expansion of irrigated agriculture (Fig. 2) and the dry climate that prevailed in the early 20th Century (the “Federation Drought”), river flows declined and seawater intrusions to Lake Alexandrina became more frequent and prolonged (Sim and Muller 2004). This led to construction of five barrages along the seaward margins of the lake completed in 1939-1940 (Plates 10, 11, Fig. 1). The barrages raised the lake level by about 700 mm (average 350-800 mm: Jensen *et al.* 2001), banking water up along the river toward Lock 1 (Senate Inquiry 2008).



Plate 10. Goolwa Barrage, from the mainland across to Hindmarsh Island, is one of a series of five barrages that stop stops seawater flowing to the Lower Lakes (R.T. Kingsford, Nov 2007).



Plate 11. Tauwichee Barrage stops seawater entering Lake Alexandrina (nearside) from the Murray Mouth and Coorong. Exposed areas are the effect of receding lake levels (R.T. Kingsford, Nov. 2009).

Lake levels usually drop in late summer, in response to increased evaporation and diversions, and rise with inflows in winter and spring. Chronic water shortages were evident in the 1990s, and have since been exacerbated, with record low inflows in 2006-2009, prompting governmental expenditure on supplying water to communities, including Adelaide (Table 2). September 2001 to August 2008 was one of the lowest rainfall periods on record for the Murray-Darling Basin, and second only to 1939-1946 (Murphy and Timbal 2007). For the two years before August 2008, annual inflows into the River Murray (3,540 GL) were about half any other recorded minimum (MDBC 2008). Total flows reaching Lock 1 were 580 GL in 2007, 534 GL in 2008 and 319 GL until August 2009 (MDBA unpubl. data).

Climatic and hydrological projections suggest that there will be additional impacts due to increased temperatures and decreased rainfall under climate change, although there is considerable uncertainty (Chiew *et al.*, 2008). Median annual runoff across the Basin is estimated to decline by 20% by 2050 under a high global warming scenario, but could decline by as much as 60% (CSIRO 2008b). The uncertainties increase substantially after 2050. In addition, additional farm dams, groundwater pumping and plantation forestry could mean that another 375 GL of surface water is intercepted (CSIRO 2008b). The proportion of the Coorong that is 'healthy' is predicted to decrease with climate change, unless freshwater flows increase, particularly under the high global warming scenario (Lester *et al.* 2009a).



Plate 12. Increasingly, large expanses of Lake Alexandrina's lake bed are exposed by dropping water levels (R.T. Kingsford, Nov 2009).

Table 2. Projected and real costs of dealing with the crisis in the Coorong, Lower Lakes and Murray Mouth and other rivers in the Murray-Darling Basin as a result of overextraction and regulation of rivers. See Fig. 1 for locations of some of the current or proposed structures.

Component ^a	Purpose or effect	Costs \$M
Pomanda Weir (2010)	Weir planned to separate the River Murray from Lake Alexandrina. Designed to secure a potable water supply for Adelaide and rural towns in the event of continued drought. A temporary structure.	160
Clayton and Currency Creek Regulators (2009)	Designed to prevent exposure of ASS by raising water levels in the Goolwa Channel and at the mouths of Currency Creek and the Finnis River. Plan for a third weir across the Finnis River mouth has been suspended after good seasonal rainfall. Initial pumping of water from Lake Alexandrina to raise the level in the Goolwa Channel.	26
Pumping of water to Lake Albert (2008)	As an interim measure water was pumped from Lake Alexandrina to Lake Albert to ensure that acid sulfate soils were not exposed. Designed to maintain level in Lake Albert by pumping from Lake Albert, abandoned in June 2009. Includes cost of embankment constructed.	>14
Dredging of Murray Mouth (since 2002)	To keep water flowing through a channel from the River Murray to the Southern Ocean.	32 (ongoing cost 5 y ⁻¹)
Rehabilitation of acid sulfate soils (2009)	To bind the soil and prevent physical disturbance, hence exposure of ASS, includes limestoning and aerial seeding of crop species.	10
Piping ^b (2009)	To supply drinking water to the towns of Narrung, Meningie, Milang and Point Sturt and irrigation water from the weir pool above Wellington	127
Option of channel from Coorong to Lake Albert (possible intervention)	Inundate Lake Albert with Coorong water and stabilise acid sulfate soils. Construction options range from an expensive structure with regulators to relatively simple channel with additional pumping costs.	2-150 ^b
Coorong – pumping from Sth Lagoon to Encounter Bay (possible intervention)	To reduce salinity levels in the Coorong and retain some of its ecological character <i>via</i> this resetting mechanism	20

^aDate built or projected dates in parentheses where known

^bIncluded as part of \$200 million, within the Long Term Plan but may not be sufficient funding

Table 2 Continued. Projected and real costs of dealing with the crisis in the Coorong, Lower Lakes and Murray Mouth and other rivers in the Murray-Darling Basin as a result of overextraction and regulation of rivers. See Fig. 1 for locations of some of the current or proposed structures.

Component ^a	Purpose or effect	Costs \$M
Planning for the future of the CLLMM (underway)	Long-term planning t(\$10 million) to identify what options exist for the changing ecological character of the CLLMM and funding of remediation	200 ^c
Desalination Plant (planned)	To ensure Adelaide's drinking water supply because of declining flows from the River Murray	>1400 Operating cost >108 y ⁻¹
Monitoring	Increased monitoring of water levels, acid sulfate soils, salinity, ecological variables	<10
Levee banks	Along 100 river-km of the Lower Murray, with cracks in levee banks from drying	20-100
Irrigation areas on Lower Murray	Expenditure lost on laser levelling and upgrading of infrastructure	60-90 ^d
Extensions of offtakes for water supply	With low river levels, pipes need to be extended to access water	Unknown
Riverbank slumping	40 separate incidences of bank slumping (100s of metres) downstream of Mannum (Harvey, P. pers. comm.). Hazard to life and vehicles (3 lost vehicles already). Increased sedimentation and erosion, impacts on terrestrial vegetation	Unknown
Government planning and Inquiries	Many Government planning processes, including Senate Inquiries	Unknown
Loss of fisheries	Likely impacts on fisheries	Unknown

^aDate built or projected dates in parentheses where known

^cCovers some of the costs of other components

^dRepresents loss of investment and probable cost of rehabilitation (Harvey, P., pers com)

Table 2 Continued. Projected and real costs of dealing with the crisis in the Coorong, Lower Lakes and Murray Mouth and other rivers in the Murray-Darling Basin as a result of overextraction and regulation of rivers. See Fig. 1 for locations of some of the current or proposed structures.

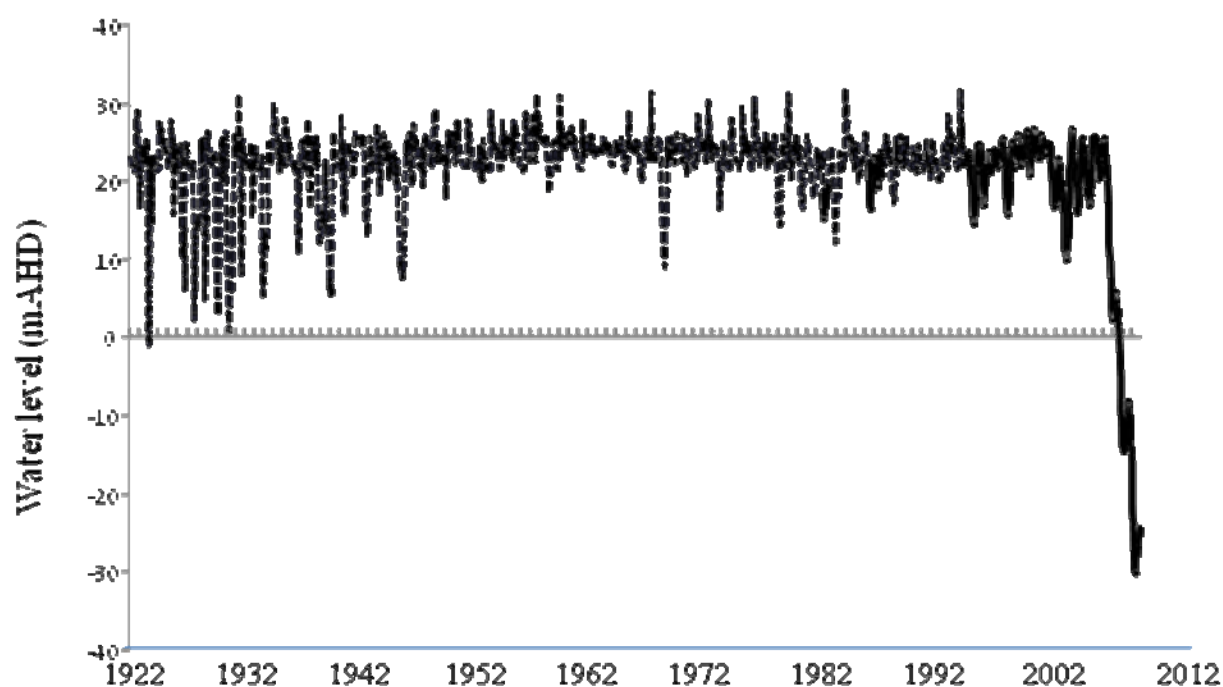
Component ^a	Purpose or effect	Costs \$M
Loss of conservation tourism	The significance of the CLLMM as a hotspot for biodiversity, particularly birds, will decline	Unknown
Loss of local irrigation	No access to water for local communities irrigating from the Lower Lakes	Unknown
Total cost of CLLMM crisis	Does not include ongoing maintenance costs	2084-2204

^aDate built or projected dates in parentheses where known

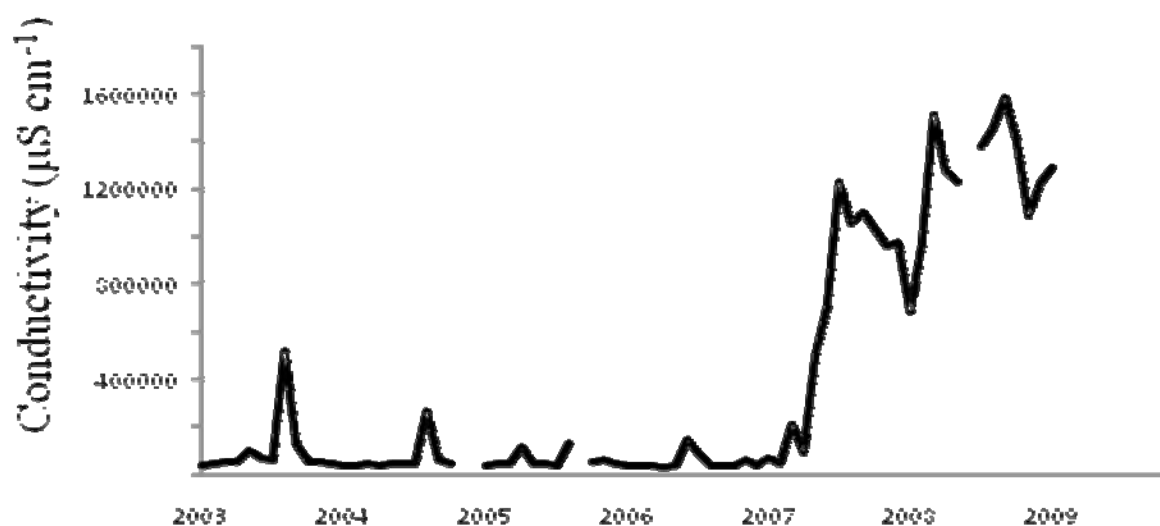


Plate 13. Salt scalds south of the South Lagoon of the Coorong show the high salinity of these habitats (R.T. Kingsford, Nov 2009).

The Lower Lakes are drying more rapidly than at any stage since 1921 (Plate 12, Fig. 3a). The North Lagoon of the Coorong is becoming more saline because the barrages have been closed since early 2007, allowing no fresh water to enter, although the salinity has decreased owing to seawater inflows in 2009. Salinities have increased throughout the Coorong, with particularly high levels in the South Lagoon (Plate 13). Seventy-five percent of the Coorong in 2005-2006 had salinity levels at least double those of sea water ($>110,000 \mu\text{S cm}^{-1}$ EC), and up to seven times seawater in the South Lagoon ($>380,000 \mu\text{S cm}^{-1}$ EC) (MDBC 2008). Current salinity levels increase away from the Murray Mouth (4 November 2009; <http://e-nrims.dwlbc.sa.gov.au/swa/>) range from $10,880 \mu\text{S cm}^{-1}$ near Goolwa Barrage to $100,078 \mu\text{S cm}^{-1}$ in the North Lagoon of the Coorong (Fig. 3b). With decreasing freshwater flows, water in the Coorong ranges from marine to salinities higher than seawater in the North Lagoon and even more saline in the South Lagoon, which has resulted in dramatic decline in species diversity and abundance (Brookes *et al.*, in review).



a.



b.

Figure 3. a. Modelled (dashed line) and actual (solid line) water levels at Milang Jetty (AHD, sea level) on Lake Alexandrina (see Fig. 1), 1922-2009. Modelled water level was based on the relationship between actual monthly water level data at Milang Jetty and monthly water level data at Lock 1 (274 km upstream of mouth), using polynomial regression fitted in R language using the LOESS function. b. Salinity (conductivity) upstream of Tauwichee Barrage (Plate 11). Water level and salinity data from (<http://e-nrims.dwlbc.sa.gov.au/swa/>).

The biota of the Lakes is changing to salt-tolerant species, particularly estuarine and marine species. The CLLMM formerly supported diverse communities of plants, waterbirds, fish and other animals, including endangered species (Phillips and Muller 2006). There were 117 aquatic and floodplain species recorded during surveys in 2008/ 2009 of the Lower Lakes 33 species less than during similar surveys in 2004/2005 (Marsland and Nicol 2009).while macrophyte abundance in the Coorong has declined precipitously (Rogers and Paton 2009a,b; Brookes *et al.* 2009, in review). The native fish community (18 species: Wedderburn and Hammer 2003) is changing as freshwater species decline (Wedderburn and Barnes 2009). In 2002, three species (Murray hardyhead *Craterocephalus fluvialilis*, Yarra pygmy perch *Nannoperca obscura*, southern pygmy perch *N. australis*) lived in areas where there were aquatic plants (Plate 14, Hammer *et al.* 2002). The Yarra pygmy perch is now considered extinct in the wild in the Murray-Darling Basin, the other two species occur only in small remnant pockets and the Murray hardyhead faces imminent extinction (Wedderburn and Barnes 2009). Diadromous fish, including common galaxias *Galaxias maculatus* and congolli *Pseudaphritis urvillii* (Plate 14), can no longer migrate between marine and freshwater environments; few galaxias and no congolli were captured in surveys in March 2009 (Wedderburn and Barnes 2009). There is a successful captive maintenance program for a number of rare small-bodied species which are surviving well in captivity.

In the Coorong, migratory shorebirds and herbivorous and piscivorous waterbirds have declined as salinities have risen (Paton *et al.* 2009; Rogers and Paton 2009a,b). Estimates of waterbirds for the CLLMM in November of 2007 were 250,000 (Plates 15-18), including 42 species identified during aerial surveys (Kingsford and Porter 2008), but in a similar survey in 2008 the numbers had declined by 48% (Kingsford and Porter 2009). As well, there were more estuarine species of waterbirds (shorebirds, terns) in the Lower Lakes in 2008 than 2007. The marine tubeworm *Ficopotamus enigmaticus* (Serpulidae) is invading previously-freshwater habitats, forming dense masses of calcareous tubes on hard surfaces (including animals with shells), killing freshwater mussels, turtles (Plate 19) and other organisms.

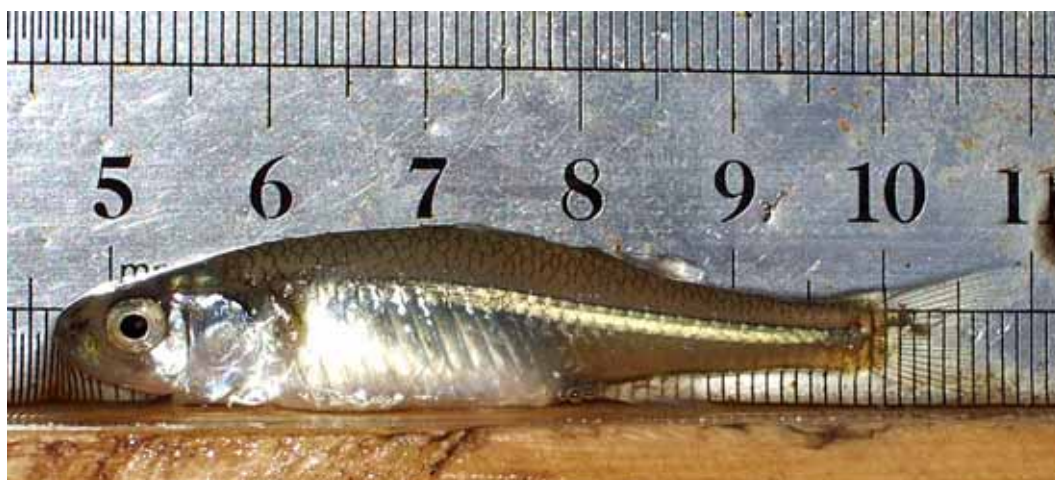


Plate 14. Small native fish of the Lower Lakes: Southern pygmy perch (upper), Murray hardyhead (middle) and congolli (lower). Photos: Dr Scotte Wedderburn.



Plate 15. Caspian terns (background) and whiskered terns (foreground) feed on the fish in the Coorong, Lower Lakes and Murray Mouth (R.T. Kingsford, Nov. 2006).



Plate 16. Australian Pelicans are found in large numbers throughout the Coorong, Lower Lakes and Murray Mouth in large numbers (R.T. Kingsford, Nov. 2006).



Plate 17. Australian Pelicans nest in large colonies on the island of the South Lagoon of the Coorong (R.T. Kingsford, Nov 2009).



Plate 18 . Banded stilts collect in flocks of tens of thousands on the Coorong (R.T. Kingsford, Nov. 2008).



Plate 19. A Murray turtle, *Emydura macquarii*, with shell encrusted by the calcareous tubules of the tubeworm, *Ficopotamus enigmaticus*. Lake Alexandrina, 2009. Photo: KF Walker.

ASS have become the main driver for engineering-focused policy and management in the CLLMM. ASS occupy about 95,000 km² of coastal Australia, including about 2410 km² in coastal South Australia (Fitzpatrick *et al.* 2008a). They have always been present in the CLLMM, and are also reported in upstream wetlands on the River Murray (Baldwin *et al.* 2006). They are a natural by-product of local climatic instability during the Holocene, with elevated levels of iron sulfides (FeS; FeS₂) that produce acidity on exposure to oxidation (Plates 20, 21), leading to extremely low soil pH. The build-up of reduced sulfur in sediments results from primary or secondary salinisation, which increases with prolonged inundation (Baldwin and Fraser in press, Hall *et al.* 2006). Acidic run-off into lakes and streams can mobilise aluminium, iron and other metals.



Plate 20. Example of acid sulfate soil mobilisation on the River Murray near the town of Berri, upstream of the Coorong, Lower Lakes and Murray Mouth (R.T. Kingsford, Nov. 2009).

ASS are not a problem for wetlands until exposed to atmospheric oxygen; this is exacerbated when the sediments are disturbed by wind, vehicles, livestock or other agents. The severity of the problem depends on the extent of exposure, hydrological conditions, the rate of mobilization of acid and the intrinsic buffering capacity of the soil and water. Soils in and around the Lower Lakes are derived from limestone, producing a pH of about 8.3 in the lake water (e.g. Geddes 1984), indicating a natural but limited capacity to neutralize acid. Sea water also has a significant buffering capacity, but could create new environmental problems through reduced alkalinity of surface waters and mass precipitation of iron oxides (Sammut *et al.* 1996). ASS potentially affect all human uses of water (recreational, drinking, irrigation) and residues may also be carried by dust. Acidified water can kill aquatic organisms through direct exposure, affecting calcium metabolism, smothering by iron precipitates and through the toxicity of aluminium and other metals (Sammut *et al.* 1995; Dove and Sammut 2007a,b).



Plate 21. Advanced acidification of Dunns lagoon in the CLLMM (SA Government, Nov. 2009).



Plate 22. Large expanses of reedbeds on Lake Albert provide vegetation for potentially stabilising acid sulfate soils on this lake (R.T. Kingsford, Nov. 2009).



Plate 23. Large expanses of reedbeds provide habitats for herbivorous waterbirds in the Goolwa Channel and Finnis River area as well vegetation for potentially stabilising acid sulfate soils on this lake (R.T. Kingsford, Nov. 2009). (R.T. Kingsford, Nov 2009).

In the CLLMM, there are predictions of extensive ASS that could be exposed at a lake level of -1.5 m AHD (Fitzpatrick *et al.* 2008b). Between lake bed levels of +.75m AHD and -1.0m AHD, there is an estimated positive net acidity area of 172 km², accounting for net acidity in the range of 250->1,000 mol H⁺ tonne⁻¹ (Seaman, R., pers. comm). In September 2009, the level of Lake Alexandrina was -0.76 m.

Prospects

The present crisis is largely caused by our past failure to adequately manage a highly variable resource. Dams were built and approved, yields estimated and licences allocated during wet periods (Kingsford 1995), with little regard for the inevitability of drought, or for environmental impacts (Kingsford 1999). As the ecological consequences emerged, governments were slow to act, protecting water rights for the prosperous irrigation industry. From 2006, decisions limiting the flow to South Australia, and ultimately the CLLMM, hastened the decline. An Interim Basin Plan from the MDBA may have averted the present crisis, but the Authority has played a minor role up to now.

In October 2009, the New South Wales Government announced allocations of 4-5% of River

Murray water entitlements on the basis that the main storages had sufficient water (Hume Dam 36%, Dartmouth Dam 28%, Menindee Lakes 12%, Lake Victoria 46%) following seasonal rainfall (DECCW 2009). There is no clear rationale for this decision in light of the problem in the CLLMM. It appears that a freshwater future is possible for the Lakes, despite projected changes in the regional climate (CSIRO 2008a). Water allocation policies have played a key role in the crisis, and they define the future of the CLLMM to an even greater extent than climate change (e.g. Lester *et al.* 2009a). Increasing freshwater flows to the CLLMM is the only solution to maintaining part, if not all, of the system's ecological character. Even small environmental allocations could be effective if timed well (Lester *et al.* 2009a). At the end of August 2008, there were 4,378-5,840 GL (24% of capacity) in upstream storages, with 1,499 GL allocated (Senate Inquiry 2008). It is not clear how much of the remaining water was either inaccessible (e.g. Talbingo Reservoir has no low-level offtake), or would not reach the CLLMM due to system losses. More rainfall in the catchments during 2009 should mean additional water for the CLLMM but this is subject to policy decisions, governed by water sharing plans.

In the long term, there are four options to increase flows to the CLLMM: (1) buy back irrigation entitlements, (2) increase the efficiency of using water extracted upstream and locally and return the savings to the river, (3) compulsory acquisition of irrigation water (by state governments) and (4) reduction in extraction levels. The Australian Government has committed \$3.1 billion to buy back irrigation entitlements for Murray-Darling Basin wetlands. The cost of Murray water now averages \$2,156 ML⁻¹ (DEWHA 2009). At this cost, \$3.1 billion could return 1,438 GL (100% expenditure), 719 GL (50%) or 359 GL (25%); this is similar to the estimate of 1,500 GL (Productivity Commission 2009). Currently, about 242 GL (average long-term volume available water) has been purchased from Murray catchments (DEWHA 2009). Most water (395 GL) has been purchased for stressed wetlands elsewhere in the Basin, notably the Macquarie Marshes, the Murrumbidgee, Lachlan and Gwydir wetlands and Menindee Lakes. There are other key wetlands along the Murray requiring water, including four other Ramsar sites: Barmah-Millewa, Hattah-Kulkyne, Koondrook-Perricoota and Chowilla floodplain. It is not clear how much Murray water will be purchased and how much of this would reach the CLLMM, given that there are significant transmission losses. In effect, allocations to wetlands remote from the point of origin require additional 'conveyancing' water factored into the allocation.

Regulation has reduced the long-term median annual flow at the barrages by 71% (Table 1), but low flows are down by considerably more, leading to disproportionate impacts during drought. These include falling lake levels, increasing salinities and the risks associated with ASS. Appropriate flow targets for low-flow periods need to be fully modelled but preliminary modelling suggests that flow should not fall below one-third of the natural flow in any year. This rule would increase the median flow at the barrages by about 700 GL y⁻¹ to nearly 3,800 GL y⁻¹, but would offer flow protection during drought. This translates to about a 6% increase in flows above current levels, shifting end of system flows to about 35% of natural. This could be managed through a series of rules that target ecosystem responses (e.g. fish passage, flooding).

There is uncertainty about the water dividend for the river from the Australian Government's expenditure of \$5.8 billion on increased water-use efficiency, and it remains to be seen how much water can be used for the CLLMM. Compulsory acquisition by State governments has not seriously been considered, in deference to the social and economic impacts. There will be an opportunity to review water sharing policies with the setting of 'sustainable diversion limits' in the MDBA Basin Plan, but this is not expected to take effect until mid-2011, and compliant State water resource plans will not take effect until 2014-2019. Defining sustainable diversion limits will be extremely difficult, but the present state of the CLLMM is clear testament that present levels of diversions are not sustainable. There is a perception that there is insufficient water in the system and that the CLLMM will be deprived of flows as global climate change progresses and eventually be inundated by rising sea levels. These risks exist but with careful management of water resources and a level of sophistication not yet approached in the management history of the Murray-Darling Basin, the CLLMM can be saved, albeit an immense challenge for communities, their governments and agencies.

There may be sufficient small flows to slow the drying of the CLLMM over the summer but if not, alteration of ecosystem states is highly likely (Lester and Fairweather 2009b). Governments have primarily responded with rapidly-implemented engineering solutions at considerable cost (Tables 2 and 3). Drivers of policy include avoidance of irreversible damage to the CLLMM, particularly through acidification, ensuring that actions do not affect water quality for major water-supply offtakes in the Murray and avoidance of treatments that compromise long-term options (Senate Inquiry 2008). Modelled acidification thresholds and triggers drive this process (Brookes *et al.* 2009, in review). The development of ASS is partly

a symptom of river regulation (Hall *et al.* 2006): the barrage operating policy of maintaining lake levels at a relatively constant 0.75 m AHD has not permitted wetting and drying phases. ASS were originally detected around the margins of Lake Alexandrina, during a national survey, with initial sampling concentrated around the mouths of the Finnis River and Currency Creek (Fitzpatrick *et al.* 2009). Based on this preliminary survey, the South Australian Government deemed the data sufficient to warrant engineering interventions, with

Table 3. Past and planned interventions (*) in the context of the evolving Long-Term Plan for the Coorong, Lower Lakes and Murray Mouth (DEH 2009), with indications of ecological consequences and management responses. The table does not include the effects of structures like dams, weirs and levees outside the CLLMM, although these do have significant effects. Figure 1 shows the locations of many of the structures listed.

Structure or Option ^a	Effect	Response
Barrages (1939-1940)	Stopped seawater intrusions to Lake Alexandrina, maintaining it as fresh water and stable, elevated water levels. Sediment accumulation, including potential ASS.	Allow flow over barrages if sufficient flow in the river to sustain lake levels. Installation of fishways.
Dredging at Murray Mouth (since 2002)	Limits sand accumulation at the river mouth and provides limited flushing and access for fish. Maintains salinity for some distance inside the Murray Mouth and maintains connectivity with the sea. Prevention of collapse of Coorong ecosystems by providing one significant source of water in the absence of freshwater flows.	To be continued indefinitely, pending return of sufficient flows in the Murray.
Weirs at Clayton (Goolwa Channel), Currency Creek (2009) and Finnis River	Possible slowing of acidification of tributaries, further loss of connectivity in the system (no fish passage), likely exacerbation of effects of ASS immediately downstream, possible mechanism for releasing water to the Coorong to support estuarine species. Possible creation of a freshwater refuge in the short term. Salinity levels likely to increase in the long term. Blocked transport of nutrients and sediments and fish movements, and has isolated the main body of Lake Alexandrina.	To be removed if/when sufficient river flows are restored.

^aDate built or projected dates in parentheses where known

Table 3 continued. Past and planned interventions (*) in the context of the evolving Long-Term Plan for the Coorong, Lower Lakes and Murray Mouth (DEH 2009), with indications of ecological consequences and management responses. The table does not include the effects of structures like dams, weirs and levees outside the CLLMM, although these do have significant effects. Figure 1 shows the locations of many of the structures listed.

Structure or Option ^a	Effect	Response
Weir ('bund') between Lake Alexandrina to Lake Albert (2008) and pumping (intermittent)	Sediment accumulation, requiring dredging. No fish passage. Possible limiting effects of acidification on Lake Albert ecology, has resulted in further loss of connectivity in the system. Maintains higher water levels in Lake Alexandrina, thereby limiting the potential impacts of ASS and drawdown for that lake. The lakes naturally disconnect at about -0.3m AHD.	To be removed if/when sufficient river flows are restored. Fish in Lake Albert (mainly common carp) are being "fished down" to offset the effects of mass mortality expected as the lake becomes more saline.
Limestoning	Intended to neutralise acidity in lake water. Literature review was done that found few effects on benthic organisms. Water quality monitoring program is in place to ensure dosage rate matches acidity generation.	Part of several smaller-scale actions. Test effectiveness in reducing ASS and continue as necessary.
Planting of semi-aquatic plants (planned for 2010), also aerial seeding of grasses (e.g. rye) (2009)	Possible biodiversity gains (via habitat provision). Possible maintenance of higher soil and or water pHs, limiting acid generation, and reduces wind erosion and exposure of new ASS.	Introduces additional carbon source to stimulate sulfate reducing bacteria
Piping of water to Lake communities	Potentially allows better management of the Lakes for ecological purposes, delivery of domestic water with less evaporative losses	Progression of water security Lake residents & towns
Diversions of freshwater from existing Upper South East Drainage Scheme to South Lagoon of the Coorong, via Salt Creek*	Reduce salinity of the South Lagoon, promote re-establishment and growth of aquatic macrophytes (<i>Ruppia tuberosa</i>) and re-establishment of invertebrate and fish populations, initially the small-mouthed hardyhead (<i>Atherinosoma microstoma</i>).	Under consideration

^aDate built or projected dates in parentheses where known

Table 3 continued. Past and planned interventions (*) in the context of the evolving Long-Term Plan for the Coorong, Lower Lakes and Murray Mouth (DEH 2009), with indications of ecological consequences and management responses. The table does not include the effects of structures like dams, weirs and levees outside the CLLMM, although these do have significant effects. Figure 1 shows the locations of many of the structures listed.

Structure or Option ^a	Effect	Response
Dredging Coorong*	Remove the physical constriction between the North and South Lagoons of the Coorong to promote mixing, therefore reducing salinity, promoting re-establishment and growth of aquatic macrophytes (<i>Ruppia tuberosa</i>) and re-establishment of invertebrate and fish populations (initially <i>Atherinosoma microstoma</i>).	Under consideration
Option for channel from Coorong to Lake Albert*	Option to avoid acidification of Lake Albert which would become more saline. Not consistent with 'a freshwater future' for the lakes. Dramatic increase in salinity in Lake Albert will cause catastrophic and irreversible change in Lake Albert ecosystems, possible acidification of water body due to input of hypersaline water. Possible effects on Coorong ecosystems of acid transport from Lake Albert.	Requires freshwater flows to replace any volumes removed, otherwise wetland will dry
Pumping hypersaline water from South Lagoon of the Coorong to Encounter Bay*	To reduce salinity levels in the Coorong and allow restoration of conditions to support waterbirds. Increased likelihood that salinities will be below tolerance thresholds for Coorong biota, likely lowering of water levels leading to disconnection from North Lagoon, depending on timing. Potential effects on the coastal dune, beach and nearshore marine ecosystem as a result of infrastructure and saline discharge.	Requires freshwater flows or careful timing to coincide with high sea levels to replace volumes removed via flows through the Murray Mouth, otherwise wetland will dry
Pomanda Island Weir*	Loss of connectivity between River Murray and Lakes, delayed return to flows resulting in longer time to ecological recovery, likely permanent changes to bathymetry & sediment characteristics as a result of 'removal' strategy. Unlikely to adequately protect fresh water in River Murray upstream.	Proposal is shelved pending a review of conditions in 2010. If constructed, the weir would be removed if/when sufficient river flows are restored.

^aDate built or projected dates in parentheses where known

Table 3 continued. Past and planned interventions (*) in the context of the evolving Long-Term Plan for the Coorong, Lower Lakes and Murray Mouth (DEH 2009), with indications of ecological consequences and management responses. The table does not include the effects of structures like dams, weirs and levees outside the CLLMM, although these do have significant effects. Figure 1 shows the locations of many of the structures listed.

Structure or Option ^a	Effect	Response
Training structures at river mouth*	Groin to divert sand and prevent blockage at the mouth. Does not allow for movement of the Murray Mouth as has happened in the past. Also likely to require pumping of sand seasonally to prevent accumulation.	Under consideration, but unlikely.
Fishways	Installation of fishways in the barrages to allow for the movement of native fish species into and out of Lake Alexandrina	Now in place, but of limited value in prevailing circumstances, given the low water levels..

^aDate built or projected dates in parentheses where known

regulators (levees) to establish high water levels in addition to applying local management to ASS hotspots with limestoning and aerial seeding to assist in bioremediation ([Table 3](#)).

Compartmentalisation of ecosystems was a consequence, beginning with the building of a weir across the channel ('The Narrows') that separates Lake Albert and Lake Alexandrina (Plate 24, [Fig. 1](#), [Table 3](#)). The lakes naturally disconnect at -0.3 m AHD. The project was approved in March 2008 and initiated in May 2008 (Senate Inquiry 2008). Pumps were installed to transfer water from Lake Alexandrina to Lake Albert, and were operated until June 2009, when it became clear that Lake Albert was continuing to dry. There has been significant accumulation of sediment in the channel, and it is likely that dredging will be needed to restore the connection between the lakes.



Plate 24. Bund wall separating Lake Albert (background) from Lake Alexandrina (foreground) built to reduce risk of acidification but contributing significantly to compartmentalisation of the Coorong, Lower Lakes and Murray Mouth (Photo R.T. Kingsford, Nov 2009).

A weir was completed in September 2009, in the Goolwa Channel from Clayton Bay to Hindmarsh Island (Plate 25). An additional low-pass regulator at Currency Creek is now complete (Plate 26) and a similar regulator on the Finnis River is planned, but construction has been delayed following filling of the Goolwa Channel and the construction of the Goolwa regulator. The proposal will be reviewed next year. Finally, the Pomanda Island weir may be built at the junction of the River Murray and Lake Alexandrina but this too is subject to further review.



Plate 25. The Clayton Weir (looking south) disconnects the Finnis River, Tookayerta Creek and Currency Creek from Lake Alexandrina, reducing the important freshwater flows to the lakes and reducing opportunities for migrating organisms to move across the whole system (R.T. Kingsford, Nov 2009).



Plate 26. The almost completed weir (now complete) (looking south) across Currency Creek reduces connectivity of flows to the Lower Lakes, affecting the migration of aquatic organisms and nutrients (R.T. Kingsford, Nov 2009).

Another option widely discussed is to open the barrages (Fig. 1) allowing marine water from the Coorong to enter the Lakes, changing the present freshwater ecosystem, primarily designed to avoid acidification of the entire lake system. This would initially change the Lakes initially into an estuarine ecosystem, quickly followed by fully marine and then even more saline conditions. The short-term consequence of opened barrages would be mortality of freshwater biota, followed by invasions of estuarine or marine species and species tolerant of even higher salinities. A further proposed remedy is to build a channel from the Coorong to Lake Albert and submerge ASS (Fig. 1, Table 3).

The long-term ecological effects of these latter short-term engineering actions would be profound and probably not reversible. Either would fundamentally change the ecology of the lakes, with the likelihood of salinity remaining at high levels because of insufficient mixing and flushing of water through the lakes and the formation of potential ASS conditions (Fitzpatrick 2008b). Another possibility is to let the system dry. This runs the risk of further acidic oxidation of pyrite in ASS and the subsequent mobilization of the oxidation products during wet periods, unless combinations of options raise the pH and stop acid movement. About 200 ha of Loveday Bay dried out and acidified.

In the absence of barrage flows, dredging of the Murray Mouth since 2002 has provided an essential source of water to offset evaporative losses. Other proposed engineering works also could have ameliorated the effect of drought, but none modelled so far (~400 scenarios) has matched the effects of freshwater flows (Lester *et al.* 2009a, b, c, d). Engineering and micro-management options may prevent system collapse in the short term, but none is an alternative to freshwater flows over the barrages. This emphasises the necessity of securing additional water for the Coorong.

Much effort is now focused on the development of a long-term plan for the CLLMM by the SA Department for Environment and Heritage, in response to \$200 million offered by the Australian Government (Table 2). The plan, now well-advanced (DEH 2009), has identified the major problems and highlights the threat of acidification and the need for increased flows from the Murray. It includes a *vision* for the CLLMM:

Our goal is to secure a future for the Coorong, Lower Lakes and Murray Mouth as a healthy, productive and resilient wetland of international importance (DEH 2009).

The plan acknowledges an ‘irrevocable’ responsibility to conserve the ecological character of the CLLMM, with regard for its environmental significance and its cultural, social, recreational and economic value. It is committed to involving all interested parties, in and out of government, including Ngarrindjeri people. It indicates that the responses will address short-, medium- and long-term needs for at least 25 years, leading eventually to a transition to a ‘marine’ environment, based on projected sea-level rises associated with global warming. The ‘freshwater future’ for the CLLMM therefore applies within limits determined by sea level, although the plan concedes that a different ecological character could result from the impacts of the current crisis. Within this time frame, the plan aims to implement best-practice adaptive management to ensure that short-term remedies do not limit future options, to secure sufficient fresh water to re-establish ecological functions and improve water quality, to restore more natural water level regimes, bioremediate ASS and restore and maintain connectivity between habitats.

Strategies for adaptive management that are currently documented are well conceived but could be improved. Strategic Adaptive Management Planning (Biggs and Rogers 2003) is a process of articulating a desired condition for managed area, through a ‘vision’ statement and identification of key attributes, and elaborated through a hierarchy of objectives that reflect these values, beginning broadly and leading to management outcomes and indicators that are measurable and reportable. All the key issues are identified in the plan. This process could be developed explicitly for each of the major objectives for the area (e.g. connectivity, management of ASS, biodiversity conservation).

The long-term plan is primarily the responsibility of the South Australian Department for Environment and Heritage (SA DEH) (DEH 2009). To encourage integration across agencies, and facilitate future development of the plan, it would be useful to establish a joint steering committee of SA DEH, MDBA and the federal Department of Environment, Water, Heritage and the Arts.

Conservation obligations

The Lower Lakes now support a diverse range of estuarine species, which were sparse during the previous five years (Brookes *et al.* in review), and freshwater habitats in the CLLMM are diminishing with the drying and increasing salinity of the lakes, reduced connectivity and increasing salinity of the Coorong. The refilled Goolwa Channel from rainfall and pumped lake water has decreasing salinities while the salinities of the lakes increase. The South

Australian Government is obliged by legislation to protect the biodiversity values of the Coorong National Park while the Australian Government has obligations under the Ramsar Convention to protect and promote wise use of the wetlands and report any likely changes to the ecological character. There is still only an admission by the Australian Government of ‘likely change’ in character, despite abundant evidence of cascading ecological changes. Further, the Australian Government may volunteer to list a site on the Montreux Record, a list of international Ramsar sites where “an adverse change in ecological character has occurred, is occurring, or is likely to occur and which are therefore in need of priority conservation action” (Ramsar 2007). On 4 August 2009, the Australian Government decided not to take any such action. No Ramsar site in Australia has ever been listed on the international public record, despite evidence that some qualify. Any listing would probably serve little practical value as resources and efforts are currently focused on the problem; there is some value at a global scale to admit that water scarcity issues are particularly difficult even for a well developed country like Australia. The Australian Government is also responsible for protecting habitats and individual migratory bird species through various international bilateral agreements (e.g. CAMBA, the Chinese Australian Migratory Bird Agreement) and these, with Ramsar responsibility, are matters of national significance under the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*. It is clear that migratory bird abundance has declined considerably within the CLLMM (Paton et al. 2009; Rogers et al. 2009). It is problematic that many of the current engineering structures, treating the symptoms of the problem, are required to be tested by stringent environmental assessment and yet diversions of flows from upstream, the main cause of the crisis, are not assessed. Conservation obligations are thus currently subordinate to industry requirements for water upstream. The imminent collapse and unsustainable state of the CLLMM reflect the lack of collective focus by the Governments of the Murray-Darling Basin on the conservation of this unique ecosystem. It also fails to meet a key objective of the National Water Initiative, signed by most governments in 2004 (Western Australia signed later), to “complete the return of all currently overallocated or overused systems to *environmentally-sustainable levels of extraction*” (IGA 2004). Without addressing the underlying cause of lack of water, the likelihood of Australia meeting its obligations for this Ramsar site are remote.

Role of science

Twenty five years ago there were signs that the impacts of regulation and abstraction on the Murray and its floodplain communities were significant (e.g. Walker 1985). Considerable work since has contributed to understanding the increasing ecological effects of diverting water and regulating the Murray with dams and weirs (Kingsford 2000a; Walker 1992, 2006). An expert panel on the River Murray in 2002 recommended that the return of an additional 1500 GL would provide a ‘moderate’ chance of restoring the health of the River Murray (Jones *et al.* 2002), but the Australian Government and the State governments committed to returning only 500 GL, mostly through engineering efficiency options. Of that 500 GL, only 133 GL of water entitlement had actually been recovered under the Living Murray Initiative by 2008 (Senate Inquiry 2008). Although the extent of the present drought could not have been predicted, there were no contingency plans. Also, because the CLLMM never had an environmental flow allocation, it had to rely on flow reaching it from upstream, which could then also be diverted from the Lower Lakes.

Current scientific effort has documented tipping points of the freshwater and estuarine ecosystem into a marine to hypersaline condition (Lester and Fairweather 2009a,b; Brookes *et al.* 2009, in review). Until relatively recently, the scientific investment for whole-system management and understanding of basic ecology was relatively poor and piecemeal. Much of the immediate engineering response to avert acidification was based on limited sampling for ASS, with little discussion of model uncertainty for extrapolations to vulnerable areas. Sampling for acidification was preliminary rather than comprehensive (Fitzpatrick *et al.* 2008b, 2009), although subsequently considerably extended, but these data were used to support assertions that the entire CLLMM would become catastrophically acidic. This continues to be the main focus for current management. The MDBA commissioned a peer review of the ASS science that was not made public, for unexplained reasons. Issues of sampling intensity, as well as uncertainty of both modelling and the capacity for ecosystems to recover from episodic acidification have not been adequately addressed. Despite this, the policy options appear to assume the worst-case scenario, and to assume that natural recovery is not possible. The Senate Inquiry concluded that “The general consensus of experts was that sea water is the less damaging option” (Senate Inquiry 2008). Plans and operations for the mitigation of acidification impacts have considered less-intrusive measures such as

limestoning and planting of terrestrial species to stabilise soil, with an increasing emphasis on large scale restoration. There was little modelling of potential buffering potential of lake water, or the potential for harmful secondary impacts induced by the proposed management scenarios. Acidification is not entirely a human-induced process; it also occurs episodically and sometimes seasonally (Hart *et al.* 1980) under natural conditions and triggers fish kills (Bishop 1980, Brown *et al.* 1983) that do not necessarily lead to long-term ecosystem damage under natural conditions. The capacity of the modified environment of the CLLMM to recover from acidification events of varying scales and frequencies, and the effects of current or proposed engineering works need to be assessed for future options as well as initiating emergency actions. The current urgency should not be a substitute for increasing our understanding of how these complex systems operate because only that will ensure preparation for new threats. As with all aspects of the ecology of the CLLMM, research must test various predictions from the many conceptual and mathematical models used as our options depend upon the veracity of modelling. Our future ability to plan and respond should be enhanced if we emerge from this crisis with wisdom. This will be contingent on availability of fresh water and management of the system. Hydrochemical modelling alone is not sufficient to inform decision-making processes or to predict the environmental outcomes of the proposed management strategies. Ecological monitoring and modelling are also required. Similarly, there was limited analysis initially of the effects of naturally regenerating vegetation communities on lake edges might have in reducing acid generation through reduction of water loss and wind erosion. More work on sulfate reduction processes and consequences of acidification is needed.

The potential ecosystem responses to acidification have not been adequately predicted or evaluated for the CLLMM. Such an evaluation needs to consider obstruction to fish passage during acidification events, and the joint effects of natural and artificial obstructions on recruitment of the aquatic biota, as well as the potential for acidic water to pool. The current focus on hydrochemical modelling ignores fish avoidance behaviour of acid and aluminium in natural, unregulated systems (Giattina and Garton 1983, Norrgren *et al.* 1991, Sammut *et al.* 1995), acute versus chronic effects of acidification, interactions between the impacts and other factors, or processes that might determine the environmental outcomes of the proposed management scenarios. Re-engineering the system to manage ASS may restrict fish escape and reduce prospects of natural recovery because of impeded fish passage. The magnitude of fish kills (and mortality of other biota) is largely dependent on the extent and

duration of acidification events (Sammut *et al.* 1995, 1996), the presence of and access to refugia, and the chemical species of aluminium and iron (Callinan *et al.* 2005; Sammut *et al.* 1995, 1996).

The remediation or mitigation of acidification and its impacts requires consideration of complex modelling undertaken for the CLLMM, a focus on managing risk and collection of field data, given the options for management. Models should account for the acidity generated by pyrite and metal hydrolysis, the storage and transport of acid, the chemical loads and chemical species of metals, the assimilative capacity of the receiving waters and the effects of current and proposed changes to the landscape and water flows, to effectively predict environmental impacts or the efficacy of management. Such models are complex and depend upon a larger suite of environmental data than are currently available from preliminary studies. Additionally, management strategies could be underpinned by clearer environmental goals with consideration of an ecosystem's capacity to recover from acute versus chronic effects of acidification, something that would have helped before the current crisis. Acute events, such as fish kills, are not sufficient indicators of the overall impact of soil acidification and a reduction in their frequency is not a reliable measure of success for any management. Fish kills often trigger community concern yet more chronic impacts go unnoticed, and negative impacts from management could similarly be overlooked. The best management practices for the CLLMM will be difficult to identify if interactions between hydrological, chemical and ecological processes are not evaluated overtly. A more rigorous process of scientific inquiry could generate less-costly management strategies with better environmental outcomes (for ASS but also other emerging threats within the region), and avoid triggering new environmental problems.

Conclusions

There are considerable costs in treating the symptoms of the current crisis, possibly up to \$2.2 billion (Table 2). The value of water for the CLLMM needs to be informed by the considerable externalities currently realised as real engineering costs and costs to community (Table 2). Governments will embark on a long-term Basin Plan (Table 2) but this is unlikely to deal with the underlying cause of the crisis. The simplistic assumption that the last resort of opening the barrages and allowing sea water into the Lakes would create a functional estuary is highly unlikely, without significant guaranteed freshwater flows from the River Murray. A functional estuary requires the mixing of saline and fresh water. There is

opportunity to introduce more variability in inundation patterns through a structured management program that allows flow of seawater and freshwater through the barrages. None of this could be done without a guaranteed environmental flow for the CLLMM that meets its primary ecological needs. Such a flow will necessarily be variable but overall volumes must be sufficient to ensure that hypersaline conditions leading to ecosystem collapse does not occur. This may require the volume of the lakes to be reduced. Without sufficient freshwater flows, CLLMM would increase in salinity and even Lake Alexandrina would become more saline than seawater within two to three years. Management would ultimately be of a drying, acidic and hypersaline system, if significant riverine flows were not available. Lake Albert is a terminal system that would likely follow a similar trajectory to the South Lagoon of the Coorong and become more saline than seawater, with only the largest floods able to flush its salinity.

Restoring connectivity in the form of freshwater flows to the CLLMM must be a priority if the communities of Australia and South Australia are to meet their conservation obligations. There needs to be action to save the Coorong, Lower Lakes and Murray Mouth, clearly articulated through a vision, goals and specific objectives, informed and evaluated by available science and monitoring data. All these processes are well underway although they could be more clearly linked in a hierarchy of objectives in the long-term plan. A hierarchy of objectives will necessarily allow some transparency in management and achievement of adaptive management planning processes (Biggs and Rogers 2003). Given that the States of the Murray Darling Basin are also in large part responsible, the problem should not reside with just these two governments but all governments of the Murray-Darling Basin need to make these considerations part of their decision-making on annual allocations.

If connectivity is not largely restored, many of the biodiversity values will be lost. A thorough cost-benefit analysis is needed to consider the effects of this course of action on the ecology of the CLLMM and its dependent communities up to a time horizon of 50-100 years. The changes are affecting the Ngarrindjeri, local industries of irrigation, dryland agriculture, commercial fishing (including cockle harvesting), tourism, small-business trading and some urban development. The current status of the CLLMM as a wetland of national and international importance is likely to decline even further without bold decisions about its future, and its dependency on fresh water.

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References

- Arthington, A.H. and Pusey, B. J. (2003). Flow restoration and protection in Australian rivers. *River Research and Applications* **19**, 377-395.
- Baldwin, D. S., Rees, G., Mitchell, A., Watson, G., Williams, J. (2006). The short-term effects of salinization on anaerobic nutrient cycling and microbial community structure in sediment from a freshwater wetland. *Wetlands* **26**, 455-464.
- Baldwin, D. S. and Fraser, M. (In press). Rehabilitation options for inland waterways impacted by sulfidic sediments - a synthesis. *Environmental Management*.
- Barnett, E. (1993). A Holocene paleoenvironmental history of Lake Alexandrina, South Australia. *Journal of Paleolimnology* **12**, 259-268.
- Biggs, H.C. & Rogers, K.H. (2003). An adaptive system to link science, monitoring, and management in practice. In: du Toit, J.T., Rogers, K.H. & Biggs H.C. (eds) *The Kruger Experience: Ecology and management of savanna heterogeneity*. Island Press, Washington, pp.59-80.
- Bishop, K.A. (1980). Fish kills in relation to physical and chemical changes in Magela Creek (East Alligator River System, Northern Territory) at the beginning of the tropical wet season. *Australian Zoology* **20**, 485-500.
- Breckwoldt, R., Boden, R., Andrew, J. (eds) (2004). *The Darling*. Murray Darling Basin Commission, Canberra.
- Brookes, J.D., Rogers, D.J., Aldridge, K.T., Deegan, B., Hipsey, M.R., Paton, D.C., Ganf, G.G., Rolston, A., Webster, I. and, Noell, C. (in review). Managing the Lower Lakes and Coorong. *Marine and Freshwater Research*.
- Brookes, J.D, Lamontagne, S., Aldridge, K.T., Bengert, S., Bissett, A., Bucater, L., Cheshire, A.C., Cook, P.L.M., Deegan, B.M., Dittmann, S., Fairweather, P.G., Fernandes, M.B., Ford, P.W., Geddes, M.C., Gillanders, B.M., Grigg, N.J., Haese, R.R., Krull, E., Langley, R.A., Lester, R.E., Loo, M., Munro, A.R., Noell, C.J., Nayar, S., Paton, D.C., Revill, A.T., Rogers, D.J., Rolston, A., Sharma, S.K., Short, D.A., Tanner, J.E., Webster, I.T., Wellman, N.R., and Ye, Q. (2009). *An Ecosystem Assessment*

Framework to Guide Management of the Coorong. Final report of the CLLAMMecology Research Cluster. CSIRO: Water for a Healthy Country National Research Flagship, Canberra.

Brown, T.E., Morley, A.W., Sanderson, N.T. and Tait, R.D. (1983). Report of a large fish kill resulting from natural acid water conditions in Australia.. *Journal of Fish Biology* **22**, 335-350.

Callinan, R.B., Sammut, J and Fraser, G.C. (2005). Dermatitis, branchitis and mortality in empire gudgeon *Hypseleotris compressa* exposed naturally to runoff from acid sulfate soils. *Diseases of Aquatic Organisms* **67**, 247-253.

Chiew F.H.S., Teng J., Vaze J., Post D.A., Perraud J.M., Kirono D.G.C. and Viney N.R. (2009) Estimating climate change impact on runoff across south-east Australia: methods, results and implications of modelling method. *Water Resources Research* **45**, W10414, doiL10.1029/2008WR007338.

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

CSIRO (2008a). Water Availability in the Eastern Mount Lofty Ranges. A report to the Australian Government from the CSIRO Murray-Darling Sustainable Yields Project. 104pp.

CSIRO (2008b). Water availability in the Murray. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 217pp.

DECCW (2009). Critical water planning for the Murray Valley. Issue 28, 15 October 2009, Office of Water, NSW Department of Environment, Climate Change and Water (<http://www.water.nsw.gov.au/Water-Management/Water-availability/Critical-water-planning/Critical-water-planning/default.aspx>, accessed 23/10/09).

DEH (Department for Environment and Heritage) (2009). *Murray Futures. Lower Lakes and Coorong Recovery. The Coorong, Lower Lakes and Murray Mouth: Managing for a health future*. Government of South Australia, Department of Environment and Heritage, Adelaide.

Department of Environment, Water, Heritage and the Arts (2009) Progress of 2008-09: Restoring the Balance in the Murray-Darling Basin Water Purchasing <http://www.environment.gov.au/water/policy-programs/entitlement-purchasing/2008-09.html> (12/10/09).

Dove, M.C. and Sammut, J. (2007). Impacts of estuarine acidification on survival and growth of Sydney rock oysters, *Saccostrea glomerata* (Gould 1850). *Journal of Shellfish Research* **26**, 519-527.

Dove, M.C and Sammut, J. (2007). Histologic and feeding response of Sydney rock oysters, *Saccostrea glomerata*, to acid sulfate soil outflows. *Journal of Shellfish Research* **26**, 1-10.

EconSearch. (2006). Economic indicators for the Lakes and Coorong Fishery 2004/2005. Report prepared for PIRSA by EconSearch P/L, Adelaide.

- Erskine, W.D., Terrazzolo, N., Warner, R.F. (1999). River rehabilitation from the hydrogeomorphic impacts of a large hydro-electric power project: Snowy River, Australia. *Regulated Rivers: Research and management* 15, 3-24.
- Fitzpatrick R.W., Powell B., and Marvanek S. (2008a). Atlas of Australian acid sulfate soils. In: *Inland Acid Sulfate Soil Systems across Australia* (Eds R. Fitzpatrick and P. Shand). pp 63-77. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.
- Fitzpatrick, R.W., Shand, P., Marvanek, S., Merry, R.H, Thomas, M., Raven, M.D., Simpson S.L. and McClure, S. (2008b). Acid Sulfate Soils in Subaqueous, Waterlogged and Drained Soil Environments in Lake Albert, Lake Alexandrina and River Murray below Blanchetown (Lock 1): Properties, distribution, genesis, risks and management. A report prepared for the South Australian Department for Environment and Heritage. pp. 168. CSIRO: Land and Water Science Report 46/08.
- Fitzpatrick, R.W., Grealish, G. Shand, P. Marvanek, S., Thomas, B. Creeper, N., Merry R. and Raven M. (2009). Preliminary Assessment of Acid Sulfate Soil Materials in Currency Creek, Finniss River, Tookayerta Creek and Black Swamp Region, South Australia. A report prepared for the South Australian Department for Environment and Heritage. pp. 24. CSIRO: Land and Water Science Report 01/09.
- Fluin, J., Gell, P., Haynes, D., Tibby, J., and Hancock, G. (2007). Palaeolimnological evidence for the independent evolution of neighbouring terminal lakes, the Murray Darling Basin, *Hydrobiologia* **591**, 117–134.
- Geddes M.C. (1984). The limnology of Lake Alexandrina, River Murray, South Australia, and the effect of nutrients and light on the phytoplankton. *Australian Journal of Marine and Freshwater Research* **35**, 399-415
- Geddes, M.C. (1987). Changes in salinity and in the distribution of macrophytes, macrobenthos and fish in the Coorong Lagoons, South Australia, following a period of River Murray flow. *Transactions of the Royal Society of South Australia* **111**, 173-181.
- Geddes, M.C. and Butler, A.J. (1984) Physiochemical and biological studies on the Coorong Lagoons, South Australia, and the effect of salinity on the distribution of the macrobenthos. *Transactions of the Royal Society of South Australia* **108**, 51-62.
- Geoscience Australia (2003). Dams and water storages 1990. GIS dataset.
https://www.ga.gov.au/products/servlet/controller;jsessionid=60F39E08CAEC0FC6DF285AF455327A1C?event=GEOCAT_DETAILS&catno=42358 (accessed 23/10/09).
- Giattina, J.D. and Garton, R.R. (1983). A review of preference avoidance responses of fish to aquatic contaminants. *Research Review* **87**, 43-90.

- Goss, K.F. (2003) Environmental flows, river salinity and biodiversity conservation: managing trade-offs in the Murray–Darling basin. *Australian Journal of Botany* **51**, 619-625.
- Hall, K., Baldwin, D.S., Rees, G., Richardson A. (2006). Distribution of inland wetlands with sulfidic sediments in the Murray-Darling Basin, Australia. *Science of the Total Environment* **370**, 235-244.
- Hammer, M., Wedderburn, S., and Westergaard, S. (2002). Freshwater fishes. Pages 54-61 in R. Brandle, editor. A Biological Survey of the Murray Mouth Reserves, South Australia. Department for Environment and Heritage, Adelaide.
- Hart, B.T., Ottoway, E.M. and Noller, B.N. (1987). Magela Creek system, northern Australia. I. 1982-83 wet season water quality. *Australian Journal of Marine and Freshwater Research* **38**, 261-288.
- Helicon (2004). *Recreational Boating Industry Development Project: Lower Murray and Lakes*. Final Report prepared for the Fleurieu Regional Development Commission Inc.
- Hera-Singh, G. (2002). Fishing Industry. In *The Murray Mouth: Exploring the implications of closure or restricted flow*, a report prepared for the Murray-Darling Basin Commission, Department of Water, Land and Biodiversity Conservation, Adelaide, pp. 21-24.
- IGA (Intergovernment Agreement) 2004. Intergovernmental agreement on a National Water Initiative between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory (<http://www.nwc.gov.au/resources/documents/Intergovernmental-Agreement-on-a-national-water-initiative.pdf>, accessed 15/11/09)
- Jensen, A., Good, M., Harvey, P., Tucker, P. and Long, M. (eds) (2001) River Murray Barrages: Environmental flows. An evaluation of environmental flow needs in the Lower Lakes and Coorong. A report for the Murray-Darling Basin Commission, pp. 118. Wetlands Management Program, Department for Water Resources.
- Jones, G., Hillman, T., Kingsford, R.T., McMahon, T., Walker, K., Arthington, A., Whittington, J., and Cartwright, S. (2002). *Independent Report of the Expert Reference Panel on Environmental Flows and Water Quality. Requirements for the River Murray System*. Prepared for the Environmental Flows and Water Quality Objectives for the River Murray Project Board, Murray-Darling Basin Commission, Canberra.
- Kingsford, R.T. (1995). Ecological effects of river management in New South Wales. In *Conserving Biodiversity: Threats and Solutions* (eds.) R.A. Bradstock, T.D. Auld, D.A. Keith, R.T. Kingsford, D. Lunney, and D.P. Sivertsen, pp. 144-161. Surrey Beatty & Sons, Sydney.
- Kingsford, R.T. (1999) Managing the water of the Border Rivers in Australia: Irrigation, government and the wetland environment. *Wetlands Ecology and Management* **7**: 25-35.

- Kingsford, R.T. (2000a). Review: Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**, 109-127.
- Kingsford, R.T. (2000b). Protecting or pumping rivers in arid regions of the world? *Hydrobiologia* **427**, 1-11.
- Kingsford, R.T. (2003). Social, institutional and economic drivers for water resource development – a case study of the Murrumbidgee River, Australia. *Aquatic Ecosystem Health and Management* **6**, 69-79.
- Kingsford, R.T. (2004). Wetlands and waterbirds of the Darling River. In *The Darling* (eds.) R. Breckwoldt, Boden, R & Andrew, J., pp 234-259. Murray-Darling Basin Commission, Canberra.
- Kingsford, R.T. and Thomas, R.F. (1995). The Macquarie Marshes and its waterbirds in arid Australia: A 50-year history of decline. *Environmental Management* **19**: 867-878.
- Kingsford, R.T. and Thomas, R.F. (2004). Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia. *Environmental Management* **34**, 383-396.
- Kingsford R.T. and J.L. Porter (2008). Survey of Waterbird Communities of the Living Murray Icon Sites - November 2007. School of Biological, Earth and Environmental Sciences, University of New South Wales. Report to Murray-Darling Basin Authority.
- Kingsford, R.T. and J.L. Porter (2009). Survey of waterbird communities of the Living Murray icon sites - November 2008. School of Biological, Earth and Environmental Sciences, University of New South Wales. Report to Murray-Darling Basin Authority.
- Kingsford, R.T., Lemly, A.D. & J.R. Thompson (2006). Impacts of dams, river management and diversions on desert rivers. In *Ecology of Desert Rivers*, ed. R.T. Kingsford, pp. 203-247 . Cambridge University Press, Cambridge.
- Lemly, A. D., Kingsford R. T., and Thompson, J. R. (2000). Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management* **25**, 485-512.
- Lester, R.E. and Fairweather, P.G. (2009a). Ecosystem States of the Coorong: An Ecosystem Response Model. Method development and sensitivity analyses, CSIRO: Water for a Healthy Country National Research Flagship, pp. 126.
- Lester, R.E. and Fairweather, P.G. (2009b). Modelling future conditions in the degraded semi-arid estuary of Australia's largest river using ecosystem states. *Estuarine Coastal & Shelf Science* **85**, 1-11
- Lester, R.E., Webster, I.T., Fairweather, P.G. and Langley, R.A. (2009a). Predicting the Future Ecological Condition of the Coorong, The effect of management actions & climate change scenarios. CSIRO: Water for a Healthy Country National Research Flagship, pp. 104.

- Lester, R.E., Webster, I.T., Fairweather, P.G., and Langley, R.A. (2009b). Predicting the Ecosystem Response of the Coorong to the South Lagoon Salinity Reduction Scheme, A report prepared for the South Australian Murray-Darling Basin Natural Resource Management Board, Flinders Research Centre for Coastal & Catchment Environments, pp. 82. Flinders University, Adelaide, May 2009.
- Lester, R.E., Webster, I.T., Fairweather, P.G., and Langley, R.A. (2009c). Understanding and Quantifying the Ecological Benefit of Dredging the Murray Mouth, A report prepared for the South Australian Murray-Darling Basin Natural Resource Management Board, June 2009 (draft), pp. 92. Flinders Research Centre for Coastal and Catchment Environments, Flinders University.
- Lester, R.E., Webster, I.T., Fairweather, P.G., and Langley, R.A. (2009d). Predicting the Ecosystem Response of the Coorong to the Coorong South Lagoon Flow Restoration Scheme. A report prepared for the Department of Water, Land and Biodiversity Conservation, July 2009, Flinders Research Centre for Coastal and Catchment Environments, Flinders University, pp. 144
- Maheshwari, B. L., Walker, K. F. and McMahon, T. A. (1995). Effect of regulation on the flow regime of the River Murray, Australia. *Regulated Rivers: Research and Management*. **10**, 15-38.
- Marsland, K.B. and Nicol, J.M. (2009). Lower Lakes vegetation condition monitoring-2008/09. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, 45pp. SARDI Publication in press
- MDBC (Murray-Darling Basin Commission) (2008). Lower Lakes, Coorong and Murray Mouth Icon Site Environmental Management Plan 2006-07. Murray-Darling Basin Commission, Canberra.
- MDBMC (Murray-Darling Basin Ministerial Council) (1996) *Setting the Cap*. Report of the Independent Audit Group. Murray-Darling Basin Ministerial Council, Canberra.
- Murphy B.F. and Timbal B. (2007). A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology*, **28**, 859-879 doi:10.1002/joc.1627.
- Ngarrindjeri Tendi (2006). Ngarrindjeri Nation Yarluyar-Ruwe Plan: Kungun Ngarrindjeri Yannan (Listen to Ngarrindjeri people talking). Ngarrindjeri Heritage Committee, Ngarrindjeri Native Title Management Committee, 56 pp.
- Norrgrén, L., Wicklund Glynn, A. and Malmberg, O. (1991). Accumulation and effects of aluminium in the minnow (*Phoxinus phoxinus* L.) at different pH levels. *Journal of Fish Biology* **39**, 833-847.
- Paton, D. C., Rogers, D. J., Hill, B. M., Bailey, C. P. and Ziembicki, M. (2009). Temporal changes to spatially-stratified waterbird communities of the Coorong, South Australia: implications for the management of heterogeneous wetlands. *Animal Conservation* **12**, 408-417

- Phillips, W., and Muller, K. (2006). Ecological character of the Coorong, Lakes Alexandrina and Albert Wetland of International Importance. Department for Environment and Heritage, Adelaide
- Pigram, J.J. (2000). Options for rehabilitation of Australia's Snowy River: an economic perspective. *Regulated rivers: research & management* **16**, 363-373.
- Productivity Commission (2009). Market mechanisms for recovering water in the Murray-Darling Basin. Productivity Commission Issues Paper, August 2009, Canberra.
- Ramsar Convention on Wetlands of International Importance (1971). especially as Waterfowl Habitat. (Iran), 2 February 1971. UN Treaty Series No. 14583. As amended by the Paris Protocol, 3 December 1982, and Regina Amendments, 28 May 1987.
- Ramsar (2007). *Addressing change in the ecological character of Ramsar sites and other wetlands*. Ramsar handbooks for the wise use of wetlands, 3rd edition, vol. 15. Ramsar Convention Secretariat, Gland, Switzerland.
- Rogers, D.J., and Paton D.C. (2009a). *Spatiotemporal variation in the waterbird communities of the Coorong*. CSIRO: Water for a Healthy Country National Research Flagship, Canberra, 57pp.
- Rogers, D.J. and Paton, D.C. (2009b). *Changes in the distribution and abundance of Ruppia tuberosa in the Coorong*. CSIRO: Water for a Healthy Country National Research Flagship, Canberra.
- Sammut, J., Melville, M.D., Callinan, R.B. and Fraser, G. (1995). Estuarine acidification: impacts on aquatic biota of draining acid sulfate soils. *Australian Geographical Studies* **33**, 89-100.
- Sammut, J., White, I. and Melville, M.D. (1996). Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulfate soils. *Marine and Freshwater Research* **47**, 669-684.
- Senate Inquiry (2008). *Water management in the Coorong and Lower Lakes (including consideration of the Emergency Water (Murray-Darling Basin Rescue) Bill 2008)*. Standing Committee on Rural and Regional Affairs. Senate Printing Unit, Department of the Senate, Parliament House, Canberra.
- Sharley, T. and Huggan, C. (1995). *Chowilla Resource Management Plan*. Final Report. Murray-Darling Basin Commission, Canberra.
- Sim, T., and Muller, K. (2004). *A Fresh History of the Lakes: Wellington to the Murray Mouth, 1800s to 1935*. River Murray Catchment Water Management Board, Strathalbyn, South Australia.
- Steinfeld, C.M.M. and Kingsford, R.T. (in review). Disconnecting the floodplain — earthworks and their ecological effect on a dryland floodplain in the Murray-Darling Basin, Australia. *Journal of Applied Ecology*
- Walker, K. F. (1985) A review of the ecological effects of river regulation in Australia. *Hydrobiologia* **125**, 111-129.

- Walker K.F. (1992). A semi-arid lowland river: the River Murray, Australia. In P.A. Calow, G.E. Petts (eds), *The Rivers Handbook*, v1. Blackwell Scientific, Oxford, pp. 472-492.
- Walker, K.F. (2006). Serial weirs, cumulative effects: the Lower River Murray, Australia. In R. Kingsford (ed.) *The Ecology of Desert Rivers*. Cambridge University Press, Cambridge, p. 248-279.
- Webster, I.T. (2005). Hydrodynamics of the Coorong and Murray mouth. Water for a Healthy Country National Research Flagship, CSIRO, Canberra.
- Wedderburn, S. and Barnes, T. (2009). Condition Monitoring of Threatened Fish Species at Lake Alexandrina and Lake Albert (2008-2009). The University of Adelaide, Adelaide.
- Wedderburn, S., and Hammer, M. (2003) The Lower Lakes Fish Inventory: Distribution and Conservation of Freshwater Fishes of the Ramsar Convention Wetland at the Terminus of the Murray Darling Basin, South Australia. Native Fish Australia (SA) Inc., Adelaide.
- 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).