MURRAY-DARLING BASIN ESSAY

Essay #6 in a series of nine by Australia's leading water experts

The past, present and future of the Coorong, Lower Lakes and Murray Mouth

Luke Mosley, Brenton Zampatti and Matt Gibbs

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Above: Aerial views of Coorong National Park on the South Australian coast. traceloiuse, iStock.

EXECUTIVE SUMMARY

The Ramsar-listed Coorong estuary, Lower Lakes, and Murray Mouth (CLLMM) region has experienced substantial ecological decline over the last century due to reduced inflows caused by river regulation and water extraction, and unfavourable hydroclimate effects and natural calamities like the Millennium Drought.

Mosley et al. conduct a critical assessment of the causes of decline in ecological health of the CLLMM region and advise on the hydrological restoration, ongoing learning, and evolution of strategies that maximise the benefits from environmental water, coupled with infrastructure improvements. They also observe that the implementation of the Basin Plan has not resulted in expected increased flow of environmental water in the River Murray, particularly at the end of system and this may, at least in part, be a consequence of climate change.

Mosley et al. propose a more automated barrage operating system, thus enabling the operation of hundreds of gates in the barrages to manage finer-scale manipulations in response to flow, tide and prevailing wind will create a 'softer', more transparent and dynamic estuarine interface. Careful adaptive management to mitigate risks of seawater intrusion that may harm the ecological, cultural and socio-economic values of the Lower Lakes will be required.

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The past, present and future of the Coorong, Lower Lakes and Murray Mouth

Luke M Mosley[1], Matt Gibbs[2], Brenton P. Zampatti[2]

[1.] Faculty of Science, Engineering and Technology, University of Adelaide, SA
[2.] CSIRO Environment, Waite Campus, Adelaide, SA

Abstract

The Coorong estuary, Lower Lakes and Murray Mouth (CLLMM) region comprises a Ramsar-listed ecosystem that supports important ecological, cultural and socio-economic values. Owing to its location at the end of the of the Murray-Darling river system, it is particularly vulnerable to hydrological alteration. Over the last century, reduced inflows due to river regulation and water extraction have led to substantial ecological decline, exacerbated more recently by the Millennium Drought (1997–2010). The CLLMM is at a critical juncture. The ongoing impacts of river regulation, combined with projections of climate change, are likely to lead to continued hydrological, ecological, social and cultural decline, unless increased volumes of environmental water are made available, alongside improved ability to deliver this water to the region. Hydrological restoration, ongoing learning and evolution of strategies to maximise benefits from environmental water, coupled with infrastructure improvements, will be key to ensuring that the ecological health of the CLLMM can improve and potentially again support the values for which the region is recognised.

Introduction

The Coorong, Lower Lakes, and Murray Mouth (CLLMM) region in southern Australia lies at the terminus of the Murray-Darling river system. The region is the home and lands (Yarluwar-Ruwe) of the Ngarrindjeri, the indigenous people of this region (Ngarrindjeri Nation and Hemming 2018) and is recognised locally, nationally and internationally for a range of ecological, cultural and economic values. From an ecological perspective, the region is of national and international conservation significance, with the Coorong being ranked in the top six waterbird sites in Australia (Paton, 2010). In 1985, it was listed as a Wetland of International Importance under the Ramsar Convention. The area is also socio-economically important, including several regional towns (Goolwa, Milang, Meningie and Narrung) and industries such as farming, tourism and fisheries.

Historical and contemporary water resource development in the Murray-Darling Basin (MDB or Basin), alongside climate change, present a host of challenges to the ecological health of the region. Simultaneously, however, improving ecological knowledge, along with an understanding of the potential ramifications of climate change, presents adaptation opportunities for the CLLMM. This essay outlines a contemporary picture of aquatic ecosystems in the CLLMM, including historical and current states, the pressures and drivers of change, and an outlook on opportunities to preserve, protect and enhance the region's ecological character and values.

Geomorphology, hydrology, water quality

Before considering current and future challenges and opportunities in the CLLMM, we first briefly outline the diverse bio-physical setting of the system. The River Murray enters Lake Alexandrina, one of two lakes, along with Lake Albert, collectively termed the 'Lower Lakes' (Fig. 1). Lake Alexandrina is a large (~65 300 ha) and relatively shallow lake with a mean depth of 2.9 m and a maximum depth of 4.8 m (Gibbs et al. 2018). Lake Albert is a smaller (~17 270 ha) and shallower (mean depth of 1.4 m) lake linked to Lake Alexandrina by a narrow channel ('The Narrung Narrows'), but with no other outlet (i.e. a terminal lake). The combined volume of the Lower Lakes at a nominal full supply level of +0.75 m AHD is ~1900 GL.

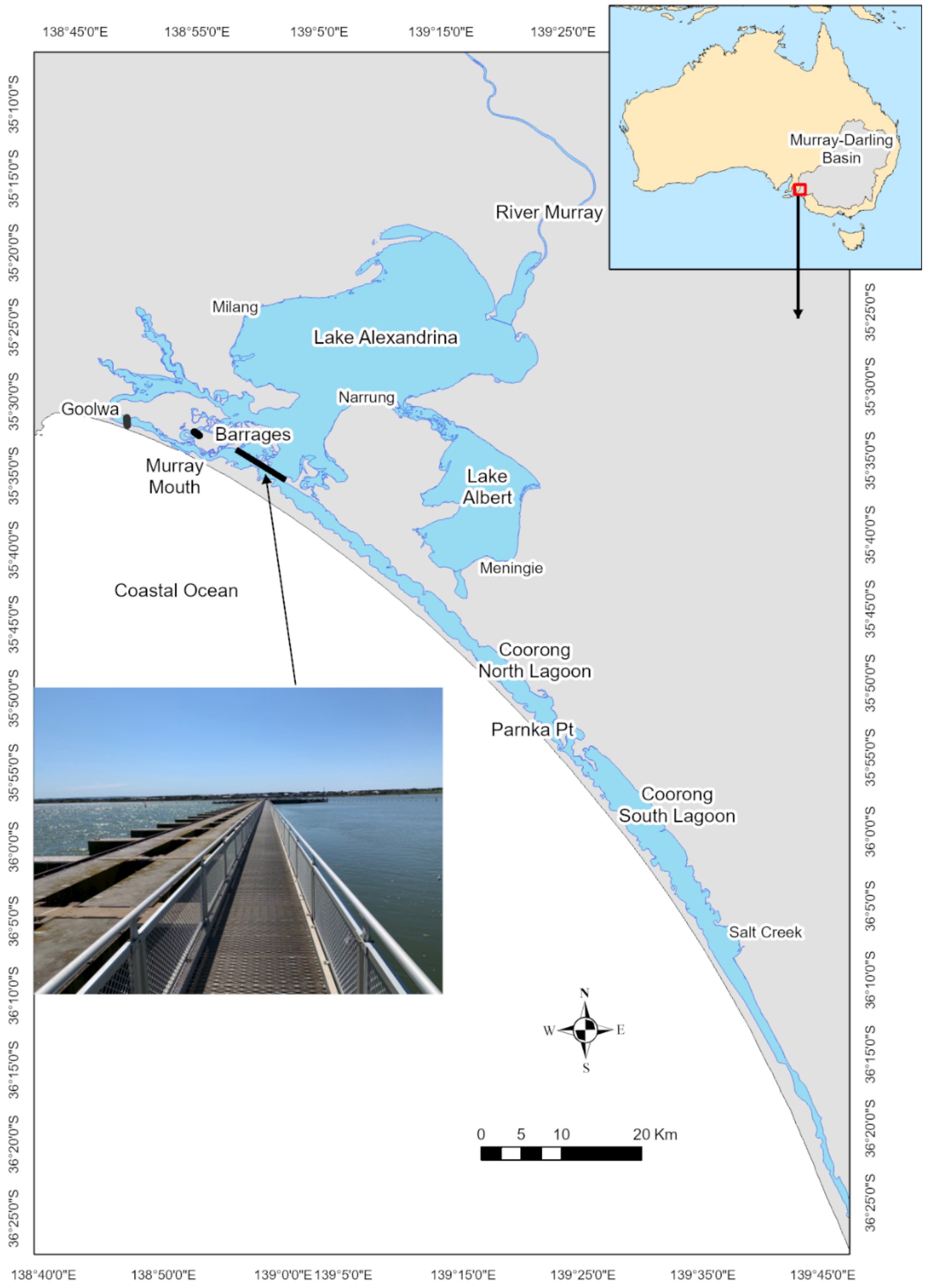

Figure 1. Map of the Coorong Lower Lakes and Murray Mouth system and inset photo of a barrage

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At the downstream end of Lake Alexandrina, a series of regulating structures known as 'the barrages' separate the freshwater Lower Lakes from the estuarine lagoons of the Coorong. The barrages were constructed over 1935–1940, to mitigate the upstream incursion of saline water, which had become more pronounced due to water resource development in the MDB, and to maintain the Lower Lakes as a body of freshwater with relatively stable water levels (Sims and Muller 2004). The five barrages have a combined length of approximately 7 km and comprise >500 individual gates that are mostly manually operated, although there are some automated gates and fishways present (Bice et al. 2017). The barrage gates are opened when suitable conditions are present, i.e. sufficient River Murray inflows to the Lower Lakes to enable freshwater outflow without lowering of lake water levels beyond normal operating ranges and to prevent incursion of saline water. Water physicochemistry in the Lower Lakes is critically dependent on River Murray inflow, with the worst water quality on record - highest salinity, algae and nutrient levels, and acidification in marginal areas - occurring in the Millennium Drought when inflows were extremely low (Mosley et al. 2012; 2014; Aldridge et al. 2018).

Once freshwater has been released through the barrages, it enters an estuarine mixing zone near the Murray Mouth, the Murray-Darling Basin's sole outlet to the ocean. Under contemporary conditions, the Murray Mouth is relatively narrow, typically 100–200 m, and has a dynamic morphology. Large outflows from the barrages deepen the Murray Mouth channel via scouring of sand (Mosley et al. 2016). In contrast, during low flows, the Mouth may completely close, as occurred in 1981 and 2003 (Gibbs et al. 2018). Since 2002, the Mouth has predominantly been kept open, mostly by near continuous dredging. Despite the Mouth being maintained 'open' by dredging, during periods of low River Murray flows, the barrages themselves may remain completely closed for long periods of time, this included 1200 days during the Millennium Drought (Zampatti et al. 2010).

The Coorong is a shallow and narrow estuarine-lagoon system (Fig. 1), which extends ~110 km to the southeast away from the Murray Mouth, separated from the sea by a sand dune barrier. It is an atypical estuary type, termed an 'inverse estuary', as salinity increases with increasing distance from the river mouth. The Coorong is typically 1.5–2.5 km wide, but its geomorphology narrows to ~0.1 km about halfway along at a narrow constriction near Parnka Point (Figure 1). The Coorong waterbody north and south of the Parnka Point region is known as the 'North Lagoon' and 'South Lagoon,' respectively. The average water depths in the Coorong are 1.2–1.4 m, with a seasonally variable volume ranging between approximately 70.1 GL and 174.7 GL at water levels of -0.3m and 0.8 m AHD, respectively (Gibbs et al. 2018). The South Lagoon also receives seasonal inputs of fresh to brackish water from Salt Creek (see Fig 1.) which connects to a network of drains from the South-East region of South Australia.

Water quality in the Coorong is determined by a balance between evaporative concentration and flushing (Priestley et al. 2022, Mosley et al. 2023). An excess of evaporation over precipitation tends to accumulate salt, nutrients and organic matter within the Coorong, but currents driven by winds and by sea level variation penetrating into the lagoon through the Mouth give rise to longitudinal mixing that transports salt and other constituents back towards the sea (Webster 2010). The Coorong is exposed to regular coastal winds that cause mixing which, coupled with the lagoon's shallow nature, results in little salinity stratification, except near the Murray Mouth during significant barrage releases (Geddes and Butler 1984).

A key driver of Coorong hydrodynamics is oceanic water-level fluctuations that lead to water exchange with the North Lagoon through the Murray Mouth. Sea levels in the adjacent coastal ocean (Encounter Bay) are mainly semi-diurnal, between 0.4 and 1.2 m during neap and spring tides, respectively, and have high wave energy (Webster 2010). The effects of tidal cycles, however, are attenuated inside the Murray Mouth and Coorong due to the restricted geomorphology. Typically, in the absence of high barrage flows creating a deep channel, the diurnal tidal ratio inside the Murray Mouth is only 0.2–0.3 m in amplitude, which declines with distance away from the Mouth (Mosley et al. 2016, Gibbs et al. 2018).

Barrage flows also play a critical role in the dynamics of water level and water quality in the Coorong by, (a) allowing sea level variations to penetrate and facilitate long-lagoon mixing of water, salt and other constituents, (b) freshening the waters of the northern half of the North Lagoon that means water of lower salt content than sea water is drawn along the Coorong to replace the evaporative loss, (c) causing a springtime rise in water level along the length of the Coorong that significantly augments and extends that due to seasonal sea level variation, and (d) helping maintain relatively high water levels in the constricted Parnka Point region allowing for enhanced wind-driven exchange between the two lagoons (Webster 2010).

The CLLMM only maintains vestiges of its former hydro-ecological character compared to the natural system prior to regulation and water diversions within the MDB. Historically, the system would have been more dynamic, with higher river inflows and a more extensive and connected estuarine zone, including in the Holocene (Tibby et al. 2022). The barrages now maintain a predominantly freshwater lake system and create a fixed and ‘harder interface’ with the estuarine mixing zone restricted to downstream of the barrages and substantially compromised connectivity between the freshwater, estuarine and marine environments. Currently, connectivity between the Lower Lakes and Coorong tends to be very limited under low flows (e.g. only fishways open), increasing as flows increase, due to more barrage gates being opened. Connectivity, however, remains much less than natural, with negative implications for populations of aquatic biota and ecosystem function.

As a consequence of hydrological change, water quality in the Lower Lakes and Coorong lagoons has also been altered significantly from historical conditions. Before the barrages were built and River Murray inflows were reduced, there was likely a larger tidal prism (defined as the volume of water contained in an estuary or embayment between the low and high tide levels). Reductions in this prism have likely had water quality implications by increasing residence time of nutrients and other constituents (Luketina 1988). Reductions in flushing of the Coorong due to reduced River Murray inflows have also resulted in much higher salinities (Webster et al. 2010) and nutrient levels in the water and sediment (Mosley et al. 2022). Nevertheless, infrequent high flows still may have a major influence on connectivity and freshening of the system. For example, with the large River Murray floods in 2022-2023, all barrage gates were opened, leading to substantial scouring of the Murray Mouth, and reductions in Coorong South Lagoon salinities to <60 psu (Department for Environment and Water, unpublished data), which is much lower than the previous two decades (Mosley et al. 2023).

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Aquatic ecosystem

Estuaries represent a unique ecotone and dynamic interface between freshwater and marine ecosystems and are considered among the world's most productive aquatic ecosystems (Hoellein et al. 2013). Globally, however, anthropogenic impacts such as river regulation and urbanisation threaten the ecological integrity of estuarine ecosystems (Gillanders and Kingsford 2002; Kennish 2002). The CLLMM region provides a stark example of a once dynamic and productive estuarine ecosystem transformed by diminished freshwater input and interrupted connectivity.

The hydrodynamics of the CLLMM are driven by tidal ingress through the Murray Mouth, freshwater flows from the River Murray and the southeast region of the Coorong, localised groundwater inputs and evaporation. The interaction of tide, freshwater flow and local hydrologic processes influence salinity throughout the system, and in turn structures biological communities. In its natural state, the unique structure of the CLLMM, including predominately freshwater lakes and a connected series of estuarine coastal lagoons, gave rise to distinct, yet spatially and temporally dynamic, biological communities. Data on the pre-European ecological character of the system are scarce but historical accounts and paleo-ecological data provide some insight. For First Nations peoples, the place where fresh and saltwater mix has profound spiritual relevance and has sustained cultural and resource needs for 10,000s years (Ngarrindjeri Nation and Hemming 2018).

Paleolimnological data and early European accounts indicate that the Lower Lakes were predominantly fresh, whilst the lagoons of the Coorong were brackish-marine (Fluin et al. 2007; Tibby et al. 2022). The interface between these environments, however, was spatially and temporally dynamic and, under periods of low freshwater input, regions of the lakes could tend brackish (Tibby et al. 2022) and the lagoons marine-hypersaline (Webster et al. 2010). Biological communities reflected this structuring of aquatic habitats and the dynamism in these. Furthermore, connectivity among these diverse habitats was not physically impeded, thus enabling the flux of biota and nutrients. Connectivity between marine and freshwaters led to the evolution of a diadromous fish assemblage of at least six species which undertake obligate migrations between riverine and estuarine-marine waters to complete their life cycle (Bice et al. 2018). The prevalence of this life history strategy indicates perennial connectivity between freshwater and marine environments (Mallen-Cooper and Zampatti 2018).

Human-induced reductions in freshwater inflows, commencing in the late 1800s, and the construction of the Murray barrages, have led to profound changes in the ecological character of the region. The barrages now present a hydrological and physical barrier between the downstream Coorong Estuary and lagoons, and the upstream freshwater lakes, and substantially reduce the area of the historical estuary (Harvey 1996). In their contemporary (post-regulation) state, the Coorong Estuary and Lagoons grade from brackish in the north to hypersaline in the south. As such there is a delineation of freshwater and estuarine-marine flora and fauna between the Lower lakes and Coorong, and the evolution of more salt tolerant aquatic biota in Coorong lagoons, particularly the South Lagoon. Nevertheless, even in their modified states, the freshwater Lower Lakes and Coorong Estuary and Lagoons are recognised nationally and internationally for their conservation significance (O'Connor et al. 2015).

A period of marked ecological change in the CLLMM occurred during the Millennium Drought in south-eastern Australia (Paton et al. 2009a, Kingsford et al. 2011). During this period, the barrages were closed and the River Murray ceased to flow to the sea for 1,437 consecutive days (Zampatti et al. 2010). At the same time, the water level of the Lower Lakes decreased to 1 m below sea-level

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(Gibbs et al. 2018). Ecological impacts were profound and included significant alterations to assemblages of flora and fauna, diminished estuarine productivity, consecutive years of failed recruitment of diadromous and estuarine species and the loss of obligate freshwater species (e.g. Yarra pygmy perch) (Brookes et al. 2015; Dittmann et al. 2015; Wedderburn et al. 2014; Zampatti et al. 2010). Migratory bird populations, which are a key component of the site's Ramsar list, were also significantly impacted (Paton 2009b). Recovery from these impacts appears to have been gradual over the past decade, although a key question is how is 'recovery' defined in a highly altered system, and is this even a viable concept in a dynamic system?

River flow for much of the past few decades has largely been insufficient to maintain an open Murray Mouth and this region is now mechanically dredged to provide connectivity between the CLLMM and the sea (Gibbs et al. 2018). Connectivity is a reoccurring theme in aboriginal and European culture, and in scientific understanding of ecological function. For commercial fishers, connectivity throughout the historical estuary was considered paramount to the productivity of key commercial fisheries species such a mulloway (Wood 2007). Subsequent declines in commercial fisheries are likely a result of a combination of factors including construction of the barrages, fragmentation of the estuary, diminished freshwater flows and the fishery itself. Full hydrological and ecological connectivity now only occurs during infrequent large floods (e.g. 2010-2011, 2022-2023 River Murray floods) when most barrage gates are opened and dredging is ceased at the Murray Mouth.

Pressures and drivers of change

An ongoing pressure on the CLLMM region relates to its vulnerability of being at the end of the Murray-Darling river system. Since water resource development commenced in the MDB in the late 1800s, end-of-system flows have declined markedly. With implementation of the *Water Act 2007* and associated *Murray Darling Basin Plan 2012,* water is being recovered for the environment. For example, Figure 2 shows the distribution of modelled barrage flows (over 1895–2009) for three modelled scenarios (see MDBA, 2012):

1. 'Baseline' representing conditions in 2009 prior to the Basin Plan.
2. 'Basin Plan' representing the improvements due to environmental water recovery from the Basin Plan when agreed in 2012 (BP2800 scenario).
3. 'Without development' which represents a natural flow regime through removing resource development in the model (e.g. storages and diversions).

The shift toward reduced annual barrage flow volume is evident as the scenario changes from near natural (without development) to a Basin Plan with water recovered for the environment, to baseline conditions, with the proportion of years with barrage flow exceeding 10,000 GL yr^{-1} changing from 53% of years under without development to 19% and 11% for the Basin Plan and Baseline scenarios, respectively. Without resource development, the modelled natural flow out of the Lower Lakes was 12,377 ± 585 GL yr^{-1} (annual mean ± standard error). Following water resource development and prior to Basin Plan implementation, there was on average 5,088 ± 585 GL yr^{-1} flow over the barrages, 41% of the natural flow. With Basin Plan implementation as modelled in 2012, the flow over the barrages is predicted to increase to 7,156 ± 597 GL yr^{-1} (58% of natural). The relative impact of water diversion, however, is much greater under low flow conditions, in contrast to the averages presented here.

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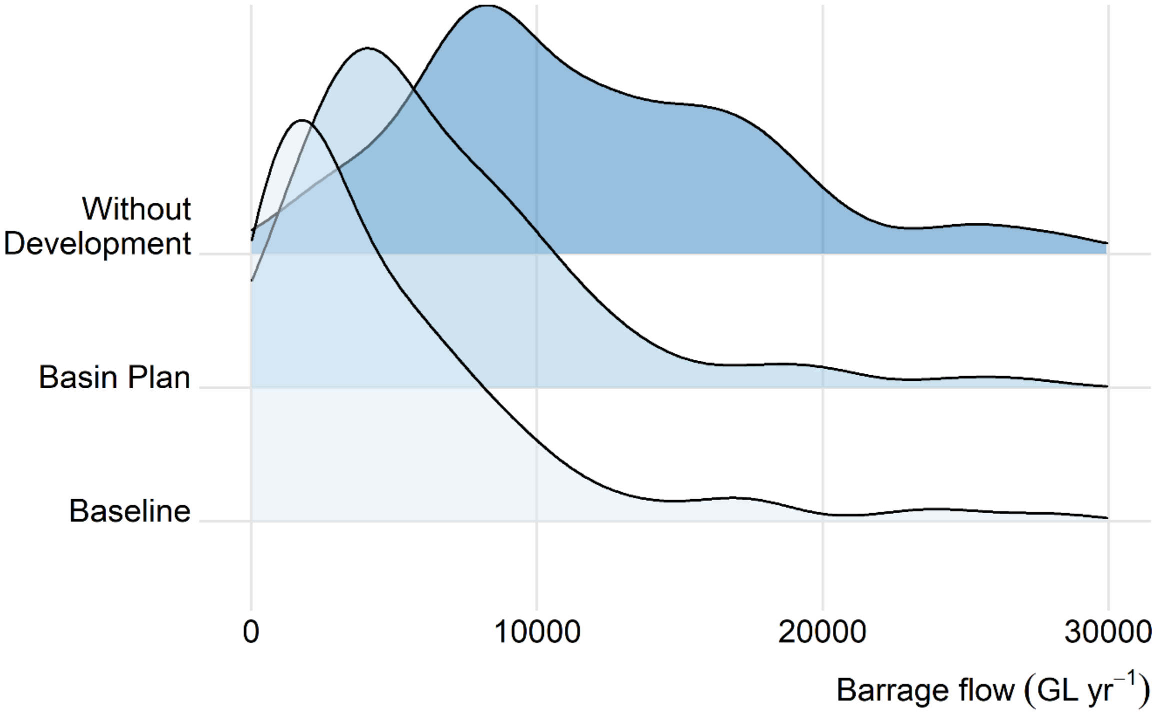

Figure 2. Distribution of modelled annual volume of barrage flow under three different scenarios, 'Baseline' representing pre–Basin Plan conditions, a Basin Plan water recovery (2,800 GL) scenario and 'without development' representing of natural conditions. Data is based on measured and modelled data from 1895-2009 provided by the Murray-Darling Basin Authority, as outlined in MDBA (2012).

Further reductions in flow are predicted due to climate change, yet this has not been considered in the Basin Plan modelling depicted in Figure 2. The 2008 CSIRO Sustainable Yields Project (prior to Basin Plan water recovery) found average surface water availability would fall by 11% and end-of-systems outflows by 24% under median 2030 climate predictions (CSIRO 2008). This study also suggested that 'At the MDB scale therefore, the largest share of the hydrological impact of climate change under current water sharing arrangements would occur at the end of the Murray River – that is, inflows to the Lower Lakes and the Coorong'. More recently, Whetton and Chiew (2020), identified that hydrological modelling studies, informed by future projections from global climate models, show a median projected decrease in mean annual runoff of 14% in the southern MDB (10–90 percentile range of -38% to +8%) by 2046–75 under the medium warming scenario. Of note, the median projected decline in runoff is similar to the volume of water returned to the environment under the Basin Plan. Furthermore, risks from more extreme scenarios also need to be recognised. For example, the MDBA (2020) Basin Plan evaluation reported that in the preceding two decades, Basin river inflows had fallen by 37% compared to the historical record. As such, whilst median projections can serve as a guide, alternative scenarios also warrant consideration.

Climate change will also promote sea level rise (SLR), another key pressure on the CLLMM that will affect this region more than any other area of the MDB. Figure 3a shows the observed SLR at the site since 1985 (based on Victor Harbor tide data), a linear projection of this rise out to 2100, and how SLR is predicted to affect the CLLMM region (Lawrence et al. 2022). The horizontal dashed lines indicate when spillways on the island between barrages are engaged. Seawater can flow over the spillways and into the lakes, at 0.83 m AHD, and the barrages structures themselves are broadly overtopped at approximately 1.1 m AHD. While the monthly average sea level is not projected to exceed these thresholds in all but the most extreme projections for 2090, the highest

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tides (defined as a water level exceeded for 6 or more hours) have exceeded these limits in the past and is projected to occur much more frequently into the future. The ability of the current barrages to maintain operations during the above sea level rise scenarios is doubtful. If the barrages are to retain their current function, these 80-year-old structures likely need to be redesigned and replaced in the face of sea level rise - we return to this opportunity below.

With significant sea level rise, some additional infrastructure may need to be built across the Hindmarsh and Mundoo Island land surfaces (Thom et al. 2020). This is also evident from inundation predictions, not considering the presence of the barrages, for a 0.6 m sea level rise scenario for the Hindmarsh Island region near the Murray Mouth (Fig. 3b), where large areas of low-lying land could be inundated. If required, there are likely to be engineering options to mitigate tidal ingress, (e. g. bunds that connect with the barrages). Nevertheless, with increased sea levels on the Coorong side of the barrages, opportunities to release freshwater from upstream of the barrages will be reduced, further limiting connectivity across these structures. Notwithstanding, the ability of coastal ecosystems and landscapes to adapt to keep pace with SLR also should not be disregarded, as there is global evidence emerging of coastal wetlands being able to keep pace with SLR where sediment and organic supply rates are sufficient (Schuerch et al. 2018).

Overall, there is uncertainty in the CLLMM region regarding the net outcome between climate change-driven reductions in inflows and increases in sea level, and water efficiency and buyback projects that are returning water to the environment. There is evidence that Basin Plan implementation has not resulted in the expected increased flow in the River Murray, particularly at the end of system (Grafton and Wheeler 2018, Colloff and Pittock 2022) and this may, at least in part, be a consequence of climate change. Hence, there is potential that the CLLMM could be worse off in the future under a changing climate compared with the late 20th and early 21st century, despite calculated water recovery under the Basin Plan. Furthermore, extreme events such as the Millennium Drought, which were modelled to be substantially mitigated through Basin Plan environmental water recovery, may again become part of the future for the region.

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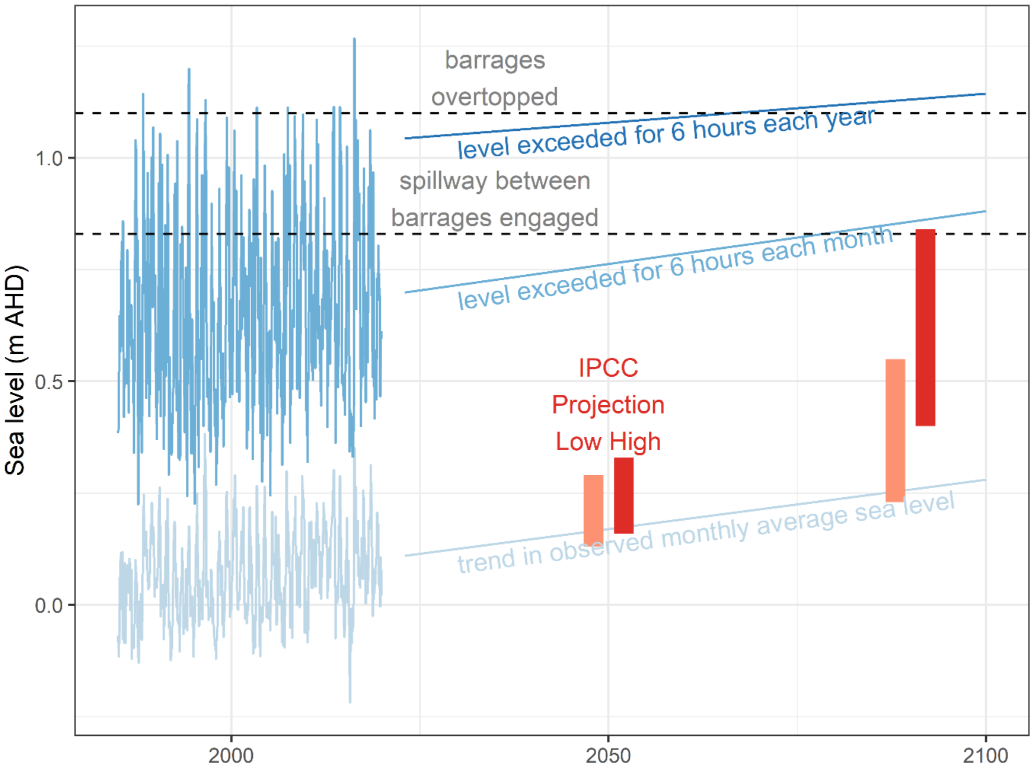

Figure 3. (a) sea level rise historic and projections with barrages overtopping. Monthly average recorded sea level at Victor Harbor (light blue) and the maximum level each month exceeded for 6 hours (blue) over the period 1963-2020. The sea level rise trend linearly extrapolated to 2100 shown as straight lines, as well as the maximum level exceeded for 6 hours each year (dark blue). AR6 IPCC projections for low (RCP 2.6) and high (RCP 8.5) emissions shown in red, along with levels where the barrages are overtopped, at the lowest point at the spillway between barrages (0.83 m AHD) and broad overtopping of the barrage structures (assumed to be 1.1 m AHD), and (b) Predicted inundation (blue areas) of Hindmarsh Island under a 0.6m sea level rise scenario (product from Coastal Risk Australia 2100 https://coastalrisk.com.au/viewer).

Opportunities and a long-term vision

In this section we explore opportunities and a future (~50 year) vision for how the values of the CLLMM region can be sustained in the face of changes that are expected to stem from climate change. Other visions have also previously been proposed for this region (e.g. Paton et al. 2009, Thom et al. 2019).

As outlined earlier, the CLLMM system, prior to river regulation, would have naturally been more dynamic, with higher river inflows and a more extensive and connected estuarine zone (Tibby et al. 2022). Our future vision is to, where possible, recreate aspects of this while managing risks that might arise. A summary of opportunities and risks is depicted in Figure 4.

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Opportunities

Review of the Basin Plan and water recovery targets.

Development of minimum flow thresholds.

New, more flexible barrage infrastructure.

Improved integration of First Nations knowledge and values.

Consideration of climate change impacts and adaptation strategies.

Improved interconnected habitat.

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Risks

Climate change and water resource development impacts:

- Reduced freshwater inflows
- Sea level rise
- Increased heatwaves
- Salinisation & eutrophication
- Ecosystem decline

Figure 4. Summary of Opportunities and Risks of achieving long term vision in CLLMM

The importance of the successful implementation of the Basin Plan for the future of the CLLMM region cannot be over-stated. Recovery and delivery of water for the environment will enable a range of benefits for the CLLMM and wider MDB. Nevertheless, in the face of climate change and predicted further reductions in run-off and river flow, the water recovery targets under the Basin Plan will likely need to be revised over time. This will be critical to maintain and rehabilitate values of the CLLMM under non-stationary climate and hydrological conditions. As documented by Colloff and Pittock (2022), however, there may be considerable discrepancies between planned water recovery, water rights acquired and ultimately, environmental water delivered, so there are residual risks with this approach. Given this, there may be merit in establishing end-of-system flow targets for the CLLMM that could be used to guide upstream water allocation, as proposed by Alexandra (2022).

It is also important to ensure future visions for the CLLMM, including Basin Plan objectives and actions, integrate Ngarrindjeri (First Nations) vision and values for the region (Ngarrindjeri Nation 2007, Ngarrindjeri Nation and Hemming 2018). Integral to this is the concept of connectivity. For example, a previous proposal to further fragment and engineer the system by constructing a twin lakes system in Lake Alexandrina was considered by the Ngarrindjeri to 'further destroy the creation of our lands and waters' (Ngarrindjeri Nation and Hemming 2018).

Proposals have been made to remove the barrages to return the Lower Lakes to a so-called 'natural state'. This does not align with the multiple lines of evidence for predominantly freshwater conditions in the Lower Lakes prior to water resource development in the MDB, and that opening the barrages under contemporary flow conditions would create major salinity risks in the Lower Lakes (Chiew et al. 2020, Tibby et al. 2020, 2022; Bourman et al. 2022). The reason for this is that the higher pre-water resource development inflows (Figure 2) were of sufficient magnitude to flush salt from the system. Mosley et al. (2021) concluded 'The current management of the barrages and water levels enables this Ramsar-listed wetland to maintain vestiges of its historical ecological character and services'. Removing the barrages would likely result in rapid and widespread loss of freshwater ecosystems and socio-economic values due to salinisation (Kingsford et al. 2019). Nevertheless, if climate change results in future 'extreme dry' scenarios, a key question concerns what salinity conditions could be maintained in the Lower Lakes?

Rather than barrage removal, it is likely that new and higher barrages may need to be considered to ensure the functionality of the barrages is maintained in the face of climate change and sea-level rise. Adaptation to climate change may also include novel solutions or other considerations such as landward retreat zones, which may be preferable if coastal marsh development can keep pace with sea level rise (Schuerch et al. 2018). Otherwise, bunds between the barrages may be needed to protect farmland and infrastructure from tidal inundation.

Rebuilding or upgrading the barrages would also present an opportunity for extensive automation of the barrage gates, thus enabling flexibility in operation that could facilitate finer-scale manipulations in response to flow, tide and prevailing wind to create a 'softer', more transparent and dynamic estuarine interface. This could:

- Provide opportunities to leave barrages open when there is a neutral or positive head difference between upstream and downstream of the barrages (i.e. higher on lakes side).
- Increase ecological connectivity, particularly important for diadromous and estuarine fish species.
- Expand the availability of estuarine habitat near the Murray Mouth, particularly under low-moderate flows.
- Increased the tidal prism to improve flushing and water quality.
- Improve the two-way flux of nutrients and carbon to better facilitate the transfer of trophic subsidies among freshwater, estuarine and marine environments.
- Provide a greater range of opportunities to push freshwater into the Coorong Lagoons while maintaining freshwater conditions in the Lower Lakes.

Implementing the above will require careful adaptive management to mitigate risks of seawater intrusion that may harm the ecological, cultural and socio-economic values of the Lower Lakes. Even when conditions may seem suitable, e. g. high river flows, there are risks of leaving the barrages open. So called temporary 'reverse flow' events have been observed, where seawater flows back into the lakes under suitable high wind and tide conditions. With relatively inflexible barrage infrastructure, as is the present case, it may take time to open/close the barrage gates to prevent these events, leading to caution in contemporary barrage operations. Nevertheless, with automated barrage infrastructure, rapid operation, based on feedback from wind, water level and salinity sensors, could enable acceptable management windows for gate opening and closure to

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be developed. Other climate change adaptation measures have also been previously considered for the Lower Lakes (e.g. Gross et al. 2012).

New infrastructure is also being scoped for the Coorong, that includes pumping options to enhance flushing of the South lagoon (DEW 2021). While these options may have the potential to reduce the long water retention times and extreme salinities experienced in the South Lagoon, from a whole of site perspective, there is a need to consider the scale of influence of these options. Ultimately the CLLMM historically functioned as a hydrologically and physically connected ecosystem and regionally specific infrastructure interventions may have minimal benefit for broader ecosystem function in CLLMM.

Hydrological and ecological connectivity with the coastal ocean is also gaining increasing recognition. Coastal productivity and food resources for seabirds have been linked to River Murray outflows (Auricht et al. 2018, Colombelli-Negrel et al. 2022). Again, a whole-of-system perspective of the CLLMM should include connectivity across the freshwater-estuarine-marine interface and the benefits of river flows to marine ecosystems. Considering the range of predicted future climate scenarios, it is unlikely that managed flow over the barrages will be sufficient to continually maintain an open Murray Mouth. As part of this, mechanical dredging of the river mouth may facilitate an estuarine-marine interface, but it is the flow of water from the river, through the estuary and into the ocean, that is necessary for ecosystem function and essential to rehabilitating the values of the region.

Conclusions

Water resource development in the MDB, and fragmentation of the CLLMM ecosystem, have led to ecological decline and compromised the values for which the CLLMM is recognised. Climate change is predicted to exacerbate these existing impacts and introduce new threats such as increases in sea level. As such, the CLLMM is now at a critical juncture. The ongoing impacts of river regulation, combined with projections of climate change, are likely to lead to continued hydrological, ecological, social and cultural decline, unless increased volumes of environmental water are made available. To this end, to potentially mitigate the impacts of climate change further reducing end-of-system flows, considerably more water for the environment may be required than that targeted in the Basin Plan. Together with hydrological restoration, ongoing learning and evolution of strategies to maximise benefits from environmental water, coupled with infrastructure improvements to improve connectivity, will be key to ensuring that the ecological health of the system can be protected and improved.

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